MEGA SCIENCE VISION 2035

Astronomy & Astrophysics

A roadmap prepared by the

Indian Astronomy and Astrophysics Community

The front and back cover pages show a colour composite image of the reflection nebula NGC 1333 obtained with the Hubble Space Telescope (courtesy: NASA/STScI).

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A roadmap prepared by

the **Indian Astronomy & Astrophysics Community**

with

IUCAA, Pune and **IIA,** Bengaluru

as

Nodal Scientific Institutions

and

submitted to

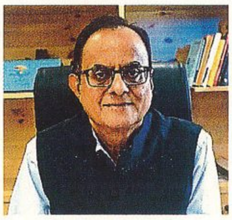
The Office of the Principal Scientific Adviser

to the Government of India

अजय के. सूद
भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
Ajay K. Sood
Principal Scientific Adviser to the Govt. of India

सत्यमेव जयते

विज्ञान भवन एनेक्सी
मौलाना आजाद मार्ग, नई दिल्ली - 110011
Vigyan Bhawan Annexe
Maulana Azad Road, New Delhi - 110011
Tel. : +91-11-23022112
Fax: +91-11-23022113
E-mail : sood.ajay@gov.in
office-psa@nic.in
Website : www.psa.gov.in



MESSAGE

It is with great pleasure that I receive the Mega Science Vision-2035 (MSV-2035) Report in Astronomy & Astrophysics (A&A). This has been formulated by the A&A community in the country, after considerable brainstorming and widespread consultations within the country, and also after eliciting the views of eminent national and international experts. May I thank IUCAA and IIA for agreeing to lead this exercise as Nodal Institutions, and our colleagues on the Drafting and Working Groups for the enormous work put in by them.

Mega Science Projects (MSPs) are intrinsically complex projects, which push the frontiers of both science and technology. They usually require large capital, human and financial resources too. Nationally, and even globally, only a few such projects are undertaken at any given time. The choice of such projects is made after vigorous national, as well as international, consultations. Such consultative exercises are periodically undertaken in all scientifically-mature nations. In India, these exercises over time have come to be known as "Vision Exercises". I am happy that the MSV-2035 Exercise this time was facilitated by the Office of PSA to the Government of India (O/o PSA to GoI). A&A are important scientific disciplines that needed to be included in the MSV-2035 Exercise, as most modern facilities employed in frontier A&A research fall into the class of MSPs.

With the advent of newer, more sensitive and more sophisticated instrumentation, A&A have seen momentous advancements and discoveries in recent times. The discovery of gravitational waves in 2016, 100 years after Einstein's General Theory of Relativity, is a revolutionary discovery employing instrumentation of mind-boggling sophistication and sensitivity that could not have been imagined some time back. This has given an entirely new tool for studying the Universe. And A&A have now graduated from multi-wavelength era to the multi-messenger era! With the wealth of data flowing in from various MSPs, we now understand the structure and processes in the Universe like never before. Not surprisingly, the A&A research community and activities have significantly expanded both nationally and globally in recent times.

The Report makes a convincing case for MSPs in A&A to be taken up by India in a lucid manner. The Report makes a case not only for participation in international projects, but also for establishing some important projects nationally. In the case of A&A, India has some internationally-competitive sites for establishing suitable observational facilities of global relevance.

I am confident that this Report will help us plan the A&A activities in the country in a systematic and informed manner. Given its comprehensive nature, it is bound to attract international attention too.

I am sure the Indian A&A community will get together and take the plan outlined in this Report forward.

Ajay K Sood

(Ajay K. Sood)

Dated: 9th May, 2024

भारत सरकार के
प्रमुख वैज्ञानिक सलाहकार के कार्यालय
विज्ञान भवन एनेक्सी
मौलाना आजाद मार्ग, नई दिल्ली - 110011

Office of the Principal Scientific Adviser
to the Government of India
Vigyan Bhawan Annexe
Maulana Azad Road, New Delhi-110011

सत्यमेव जयते

डॉ. (श्रीमती) परविन्दर मैनी
वैज्ञानिक सचिव

Dr. (Mrs) Parvinder Maini
Scientific Secretary

FOREWORD

The Mega Science Vision-2035 (MSV-2035)-Astronomy & Astrophysics (A&A) Report, is the second report of the MSV-2035 Exercise that has been facilitated by the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI). The first Report to appear was in the area of Nuclear Physics. Given the large collaborative and multi-agency nature of Mega Science Projects (MSPs), the MSV-2035 Exercise is an intense exercise involving dedicated efforts of many experts in the field. Contemporary research at the frontiers of A&A requires MSPs in a big way, and it was natural for A&A to figure as a prominent discipline to be considered under the MSV-2035 Exercise.

The Report puts forward a roadmap for MSPs in A&A in India in a reasoned and systematic manner. It highlights the leading questions in contemporary astrophysics research. It also brings out the global and national efforts being made to answer some of the important questions employing astronomy-facilities and "astronomical-messengers" or signals of different kinds. A list of international and national MSPs is proposed for India. The Report estimates the budgetary requirements and timelines of such long-duration projects, and also prioritizes them in a reasoned fashion. Reaching a nation-wide consensus regarding these is not easy, but the Drafting and Working Groups (DG and WG) have done a commendable job. A list of industries where technology-capacity-enhancement has happened as a result of participation in MSPs so far has also been included. The Report discusses in detail the A&A research eco-system in the country and presents some interesting data about researcher-profile and publication trends. It offers valuable suggestions about building a strong eco-system to support such ambitious projects, including manpower training, outreach etc. Views on management of MSPs in the country, and industry-academia collaboration have also been put forward. In general, it is a comprehensive report that has been finalized by the A&A community of the country after widespread national consultations, and with inputs from eminent national and international experts as well.

Needless to say, this Report has been made possible by the enormous work put in by the DG and WG in A&A, set up by the O/o PSA to GoI. Our deep appreciation for the co-Chairs of the WG — Prof. Somak Raychaudhury initially and later Prof. R. Srianand, Directors of IUCAA, and Prof. S. Annapurni, Director of IIA, for leading the Exercise in A&A.

We would like to also thank Dr. Praveer Asthana, PSA Fellow, and Dr. Arun Bhardwaj, Scientist-F, who anchored this activity in the O/o PSA to GoI, and made valuable contributions by way of providing legacy information and by putting this Exercise in its wider national and historical context.

I am sure this Report will prove valuable for planning national R&D activities in A&A by researchers and funding agencies alike.

PMaini

(PARVINDER MAINI)

Tel: +91-11-23022090 Fax : +91-11-23022116 E-mail: parvinder.maini@gov.in Web: http://www.psa.gov.in

ABOUT THE MEGA SCIENCE VISION-2035 EXERCISE

Mega Science Projects (MSPs) are scientifically and technologically complex projects, requiring collaboration among scientists, engineers, technicians, project managers, funding organizations, industry, etc. on a large scale – occasionally from institutions and organizations in different nations across the world. MSPs, quite often, are also large in physical size and require large monetary, capital, human and intellectual resources. MSPs are also very long-term engagements – typically taking ten years for planning, another ten years for construction and, finally, remaining in operation anywhere from 20-50 years. It follows as a corollary that, at any given time, only a few such projects can be taken up nationally, or even globally.[1]

It is natural that the decision regarding which projects to launch nationally, or which projects to participate in internationally, is always taken through wide national consultations among the concerned scientific communities. This is the way it is done the world over. And, this is the way it has been done in India, at least over the past three decades. Such structured and periodic national consultations in India have been known by several names in the past. From some point of time, they have come to be known as "Vision Exercises". Since the disciplines of nuclear physics, high energy physics and accelerator science and technology and applications were the first to experience the need for MSPs, the Vision Exercises in India in the past were facilitated by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST). In the case of Astronomy & Astrophysics, the Astronomical Society of India has been periodically organizing such exercises.

In the Indian context, by 2020, a number of MSPs that had been identified in the earlier Vision Exercises had moved further towards funding and implementation. It was, therefore, felt that a time had come to carry out the next Mega Science Vision (MSV) Exercise. It was also realized that the country had travelled a long-way from the days of India-CERN Collaboration, which could aptly be called the turning point for India's engagement with MSPs. There were a number of national as well as international projects which India had nationally launched, or in which India was participating internationally. The concerned scientific communities in India had also grown more confident and ambitious about getting involved in more such projects. Also, large collaborations had become necessary in a number of other science disciplines too. It was, therefore, decided to make the MSV Exercise more structured, inclusive and comprehensive.

In consultation with DAE and DST, which had been facilitating such exercises earlier in a few disciplines, it was decided that it would be better if the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI) facilitated the Exercise this time – given its pre-eminent S&T policy-making and coordination role in the GoI. The centre of activities thus got shifted to the O/o PSA to GoI. The O/o PSA to GoI decided that the Exercise this time would be carried out not only in Nuclear Physics, High Energy Physics, Astronomy & Astrophysics and Accelerator Science & Technology and Applications, but also in two additional areas, viz. Climate Research and Ecology & Environmental Science. Both these areas also require large-scale experimentation, data-gathering and analyses, and in many ways have been involved in MSPs without calling it by that name or realizing the same. The outcome of the MSV Exercise was expected to be comprehensive Roadmap Reports, one in each of the six areas. Given the typical time frame of MSPs, 2020-35 was decided as the period of focus for this MSV Exercise. Hence was born the Mega Science Vision-2035 (MSV-2035) Exercise in the six areas mentioned above.

For carrying out the MSV-2035 Exercise in Astronomy & Astrophysics (A&A), the O/o PSA to GoI requested the Inter-University Centre for Astronomy & Astrophysics (IUCAA), Pune and the Indian Institute of Astrophysics (IIA), Bengaluru, to act as Nodal Institutions, to which they readily agreed. IUCAA and IIA also nominated Prof. R. Srianand of IUCAA as the Nodal

Scientist. In consultation with IUCAA and IIA, a Working Group (WG) was constituted with the Directors of the two institutions as co-Chairs, and with Prof. R. Srianand as the Member-Secretary (towards the end of the MSV-2035 Exercise in A&A, Prof. Somak Raychaudhury left IUCAA, and Prof. R. Srianand became the co-Chair of the WG as the new Director of IUCAA. He also continued to take care of the responsibilities of the Member-Secretary as the A&A Exercise was almost complete.). A smaller sub-group of the WG acted as the Drafting Group (DG). The O/o PSA to GoI also laid down the goals of the Exercise and the methodology for national as well as international consultations during the Exercise.

The DG made exemplary effort in putting together several drafts of the document by reaching a large number of leading researchers in A&A in the country, and after consulting similar roadmap documents of other leading nations like Australia, European Union, Japan, USA, etc. The WG also met several times to look at the evolving drafts and offered valuable suggestions. A discussion was also organized among all the six WGs to exchange ideas about several issues that were common to all the six disciplines — for example, management structures for MSPs, aspects of fund flow, human resource development, outreach efforts, etc. Finally, a draft of the MSV-2035-A&A Report got evolved which was approved by the WG for wider national consultations. Comments on the Draft Report were electronically invited by sending the link of the webpage by e-mail to about 1000 researchers working in A&A and other proximate areas in the country. About 60 comments were received and the draft was further modified in view of those comments. In the final leg of the consultative process, a group of 19 eminent national and international astronomers and astrophysicists was set up by the co-Chairs of the WG, the Draft Report was sent to them in advance and finally discussed with them in a virtual meeting. The draft was once again revised based on the comments made by them during the meeting. The draft so developed was presented before the PSA to GoI and the Scientific Secretary in the O/o PSA to GoI, prior to its submission, and their comments and suggestions were also incorporated to the maximum possible extent. After all these steps, this final MSV-2035-A&A Report has emerged.

This MSV-2035-A&A Report is a “Roadmap” prepared by the national A&A community outlining their hopes and aspirations for mega science activities till 2035, as best as they can foresee today. Needless to say, if there are some momentous changes in the field in this period, it might change some of the projections contained in this Report. And, a similar Exercise will again take place after another 5-6 years where this Report will get updated.

It must be emphasized that this is a ‘A&A community document’, the preparation of which has been facilitated by the O/o PSA to GoI. Apart from putting the Report on the PSA Office website, it is planned to circulate the Report to various Ministries/Departments and Funding Agencies. It is sincerely hoped that the Report will be found useful by everyone associated with MSPs in the country in any manner. It is also hoped that the Report will be found useful by the international A&A community as well.

(PRAVEER ASTHANA)
PSA Fellow, O/o PSA to GoI

1. Asthana, P., Mega Science Programme in India – evolution and prospects, *Current Science*, 2022, **123**, 26.

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PREFACE

Research in Astronomy and Astrophysics (A&A) is witnessing a major revolution thanks to several international wide-field surveys, multi-wavelength space missions and multi-messenger mega projects, and the ever growing computational techniques and computing power. The Indian astronomy community is today poised to be a crucial part of the global advancements with its own facilities as well as through participation in some of the international endeavours. Vision Documents are important for any community to identify thrust areas and define priorities that provide a focused progress in science and technological advancement. While individual organisations have had their own vision documents, a community-wise exercise for A&A in India was carried out by the Indian Academy of Sciences in the year 2004. It is extremely gratifying to note that several important recommendations mentioned in the 2004 document have been well implemented. In December 2020, the Office of the Principal Scientific Adviser to the Government of India formed six Working Groups for preparing Mega Science Vision (MSV) reports for the country in six areas, with Astronomy & Astrophysics being one of them. The mandate, in brief, was: (a) to report the state-of-the-art in the field and make a strength, weakness, opportunities and threat (SWOT) analysis for India in the time window of 2020–2035, (b) to enunciate the need for continuing and undertaking new Mega Science projects, (c) to examine the relevance of such Mega Science programmes for India's scientific and technological goals, and (d) to suggest appropriate evaluation, funding and management structures for such programmes. While this charge was given to the Drafting Group and the Working Group members, there was a community-wide consultation exercise, reaching out to a very large fraction of the A&A community in India, who actively contributed to developing the document.

Modern astronomy in the country can be traced to the setting up of the Madras Observatory in 1786, which later moved to Kodaikanal with the establishment of the Kodaikanal Observatory in 1899. These observatories led to the production of "The General Catalogue of 11000 Southern Stars" in 1843, the discovery of the "Evershed Effect" from Kodaikanal in 1909 and participation in the global Carte du Ciel effort by the Nizamiah Observatory (Hyderabad) during 1914–1938. Post-independence, the efforts of renowned observational astronomers such as Vainu Bappu, Govind Swarup, V. Radhakrishnan, Arvind Bhatnagar (to name a few) led to the establishment of (then) state-of-the-art observing facilities in the country. The establishment of the optical observatories in Kavalur and Nainital in the late 1960s / early 1970s led to the discoveries of the atmosphere around Jupiter's moon Ganymede, the outer rings of Uranus and asteroids. Though early radio observations began in the 1950s, it was the setting up of the Ooty Radio Telescope and the Gauribidanur Radio Telescope in the 1970s, that led to significant developments in radio astronomy in the country. The 1980s saw the development of the 2.3m Vainu Bappu Telescope. This indigenous optical telescope was the largest optical telescope in Asia, when commissioned in 1986. The Giant Meterwave Radio Telescope (GMRT), yet another indigenous, world-class facility, was built in the following decade, and has been available to the national and international community since 2002. India's first astronomy space mission AstroSat, launched in 2015, is yet another indigenous development widely recognised and utilised by the international community. The recent success of India's solar mission Aditya-L1 has firmly established India as a key player in space astronomy.

Theoretical astrophysics is an area where India has made significant contributions, ranging from solar physics, stellar astrophysics, galactic dynamics, to extragalactic astronomy, gravitation and cosmology and gravitational waves. There have also been many contributions in computational modelling of astrophysical processes in all of these areas as well as in processing of large data sets. Indian scientists have produced many seminal works, especially in the area of gravitation and cosmology. The works by stalwarts such as Bishveshwar Dutt, V.V. Narlikar, A. K. Raychaudhuri, P.C.

Vaidya, C.V. Vishveshwara and J.V. Narlikar stand testimony to this.

The scientific achievements of the country in the field of A&A have also led to our participating in a few frontline international mega-projects expected to be operational in next few years and also development of newer state-of-the-art national facilities. The A&A community in the country is on a rapid growth curve, with a significant growth seen in the past two and half decades. The MSV-2035 document presented here has been prepared against this backdrop. It is realized that the outcomes of past investments in such programmes need to be fully exploited and international partnerships leveraged to increase the national technology-capacity in highly specialised areas in collaboration with industries. Complementary national initiatives need to be undertaken. While the proposed plans would require an increase in research funding for A&A in the coming decade, it, in turn, would certainly allow the large pool of existing (and future) young scientists to take up worldwide leadership role in A&A research, address some of the fundamental science questions, and further create a unique talent pool for development of science and technology in the country in the long term. This, eventually, would also lead to some components of basic science research being translated to applications for societal benefit.

WORKING GROUP (WG-A&A)

Nodal Institutions: IUCAA (Pune) and IIA (Bengaluru)

Dr. Somak Raychaudhury / Dr. R. Srianand (Director, IUCAA, Pune)	Chairperson
Dr. Annapurni Subramaniam (Director, IIA, Bengaluru)	Co-Chairperson
Drafting Group	
Dr. G. C. Anupama, IIA, Bengaluru	Member
Dr. Jasjeet Singh Bagla, IISER-Mohali	–do–
Dr. Ritaban Chatterjee, Presidency University, Kolkata	–do–
Dr. Shashi Bhushan Pandey, ARIES, Nainital	–do–
Other Expert Members	
Dr. Yashwant Gupta, TIFR-NCRA, Pune	–do–
Dr. D. K. Ojha, TIFR, Mumbai	–do–
Dr. Anandamayee Tej, IIST, Thiruvananthapuram	–do–
Dr. Dibyendu Nandi, IISER-Kolkata	–do–
Dr. Sanjit Mitra, IUCAA, Pune	–do–
Dr. Hum Chand, Central University of Himachal Pradesh, Dharamshala	–do–
Agency Representatives	
Dr. K. K. Yadav, BARC, Mumbai (Nominee of Chairman-AEC/Secretary-DAE)	–do–
Shri Gaurav Aggarwal, DST, New Delhi (Nominee of Secretary-DST)	–do–
Dr. V. Girish, ISRO, Bengaluru (Nominee of Secretary-DOS)	–do–
Representatives of O/o PSA	
Dr. Praveer Asthana, PSA Fellow & National Coordinator	–do–
Dr. Arun Bhardwaj, Scientist-F	–do–
Nodal Scientist - Dr. R. Srianand, IUCAA, Pune	Member-Secretary

EXECUTIVE SUMMARY

Research in Astronomy and Astrophysics (A&A) is set for a major revolution in the coming decades, thanks to international mega projects such as the recently launched James Webb Space Telescope (JWST), the future Vera Rubin Observatory's 8.4-meter Simonyi Survey Telescope, the extremely large telescopes such as the Thirty Meter Telescope (TMT), the Square Kilometer Array (SKA), future Gravitational Wave detectors (LIGO A+, Einstein Telescope, LISA), etc., and the ever improving computational techniques and computing and storage facilities. Unlike in the past, today, the Indian astronomy community is poised to be an important part of the global advancements, through its participation in some of these projects. This, together with the planned national large facilities, upgrades and efficient management of existing facilities, will allow the Indian astronomers to address some of the outstanding questions in the areas of (i) fundamental physics, (ii) early Universe and cosmology, (iii) galaxy formation and large scale structure, (iv) nearby galaxies, (v) Milky Way galaxy and its interstellar medium, (vi) cosmic chemistry, (vii) compact objects and black holes, (viii) transient and time-domain multi-messenger astronomy, (ix) exo-planetary science and (x) solar physics.

Some of the key science cases (not in any order of preference) highlighted by the community include:

- Evolution of fundamental physical constants.
- Validity of Einstein's theory of gravity in all conditions.
- Nature of dark energy and dark matter.
- Creation and evolution of the early Universe.
- Formation and evolution of galaxies and large scale distribution of matter.
- Super-massive black holes and their relation with the host galaxy.
- Transients and time domain astronomy.
- Star and planet formation and chemodynamics of the Galaxy.
- Characteristics of exo-planets and search for bio-signatures.
- Solar activity and its impact on the space environments of solar system planets.

A detailed account of various important science questions that remain unanswered is provided in this document. We provide information on how the international community is trying to address the fundamental questions in the field, the present status of A&A research in India and our own efforts to address these questions using national facilities and through participation in large international collaborations. We also provide recommendations for wider reach and growth of the community in the country.

The A&A community in the country is on a rapid growth curve, with a significant growth in the past two and half decades. This includes growth in the number of astronomers in research institutes, as well as a gradual increase in the number of astronomers working in universities and other educational institutions. This has also led to a rapid increase in the number and quality of research publications, at a growth rate doubling nearly every eight years. We can expect a steady growth in the future too, but, in order to ensure high quality, it is essential that a number of steps be taken. This aspect is also addressed here.

Recommendations: The coming decades will be the era of multi-wavelength and multi-messenger astronomy. For Indian astronomy to be in the same league as the rest of the world, it is important to have access to large observing and high-end computing facilities. This document makes several recommendations in this regard. The salient recommendations are provided here.

- It is important for India to have access to the best multi-wavelength and multi-messenger observing facilities, through international collaborations.
- For the success of A&A Mega Science Projects, it is important to adhere to all the commitments (monetary and in-kind contributions) and provide deliverables of the required quality and in required quantity on-time over the full duration of the projects.
- It is important to bridge the gap between the largest optical telescope (3.6m Devasthal Optical Telescope) presently available in the country and the TMT that will be operational in a decade's time. Therefore, it is imperative that we develop our own 10-meter class facility and/or participate in other 10-meter class telescope projects.
- Given the limited resources in our country, it is important to upgrade and operate our existing astronomy facilities efficiently. This document provides some suggestions in this regard. In particular, automation and networking of some of the facilities fitted with well thought-out instruments will enable Indian astronomers take gainful advantage of the geographical location in areas of time-domain astronomy.
- With the successful launch and continued operations of AstroSat, India has joined the small league of countries operating space observatories. It will be important to plan and exploit the window of opportunities (such as in UV and X-ray) in space to make unique contributions.
- A ground-based facility for solar observations complementing the space observatory Aditya-L1, successfully launched in September 2023 is the need of the hour to maintain India's rich heritage in Solar astronomy.
- State-of-the-art facilities require technological advancements. It is therefore important to fund new-technology and proof-of-the-concept R&D projects.
- It is now an established fact that well-maintained data archives considerably enhance the scientific output from astronomical observations. It is strongly recommended to maintain a centralized data archive for all the Indian facilities. Well-structured data pipeline facilities are needed to provide nearly uniform quality processed data to the community.
- It is important to have large, dedicated computing facilities to achieve maximum scientific outputs from astronomical observations. In particular, more realistic simulations are needed to interpret data from large

observing facilities. Setting up a national computing facility that caters to the needs of all the mega science projects will yield best results with optimum utilisation of resources.

- It is important to build a community with expertise in astronomical instrumentation, that can build large, high-precision instruments. As observatory-class facilities run for several decades, their continued relevance and success depend on instrument upgrades. It is important for the Indian community to be in a position to propose and build instruments with evolving technologies in the coming decades.

- An inclusive growth of human resources is essential for optimal use of the future facilities. While the past decade has seen good growth in the number of astronomers as well as the scientific output, there clearly is a need for enhancement and increase in the number of organisations where research and teaching in A&A are undertaken. We especially need to expand beyond research institutes and centrally funded institutions like IISERs and IITs and ensure increased presence of A&A in universities and colleges.

- Involvement of mega projects in developing modules for astronomy, physics and technical courses in colleges and universities will help familiarise students across the country with the science and technology behind large projects, and will also help attract them to A&A. The technical modules can range from data science to prototypes for structural and electronics aspects.

- Translation of scientific outcomes to evolve technologies for societal benefits and dissemination of scientific outcomes should be an important and integral part of all mega science endeavours.

Priorities: This document also prioritises the proposed projects in different wave bands.

- The highest priority for funding in the next decade should be accorded to the three A&A mega projects (TMT, SKA and LIGO-INDIA) already identified by the funding agencies. These observatories (in particular SKA and TMT) are expected to be in operation for at least 3 more decades.

- Indian optical astronomers have proposed a 10-meter class National Large Optical-IR Telescope (NLOT). This will fill the gap between the existing 3.6-meter telescope and the TMT, and enable efficient use of the TMT. It is important to support such a project to utilise the expertise gained from our participation in the TMT and enhance the technical capabilities of the Indian astronomy community and the industries.

- Solar astronomers have proposed a 2-meter National Large Solar Telescope (NLST). This will be the largest solar telescope in the country. We recommend this as the highest priority project in solar astronomy.

- It is important to enhance the sensitivity of GMRT (eGMRT) to evolve this facility as a part of global network at low radio frequencies.

- There is a need to enhance our capabilities in multi-wavelength observations, expanding to the sub-mm and high energy ɤ-ray regimes.

- Funding should also be made available for developing new-technology or proof-of-the-concept projects as well as detailed proposals for new projects.

1 INTRODUCTION

Astronomy is all about the study of the Universe. As a basic science, astronomy has links to other branches such as mathematics, physics, chemistry, computer science, materials science and biology. Primarily driven by observations, it benefits from and also drives technological advances. Multi-wavelength and multi-messenger astronomy in the recent times have been able to provide unprecedented information about the evolution of the Universe. Theoretical studies confronted by observational data lead to an improved understanding, which in turn is used to refine theoretical models of various processes and phenomena. The combination of the observational and theoretical efforts in the field of astronomy and astrophysics has also led to the development of many allied branches like nuclear astrophysics, astro-chemistry, astro-biology, etc. The advancement in technology leading to high precision data has, in addition to improving our understanding of the Universe, also thrown up several new questions and challenges.

Astronomy & Astrophysics research in India covers a wide range of topics from understanding various details of the nearest star, our Sun, to the origin and evolution of the Universe. Significant contributions have been made by Indian astronomers in theoretical studies of black holes, gravitational waves, the cosmic microwave background and the large scale structure of the Universe. The latter half of the last century saw the establishment of new observatories and development of facilities in optical, near-IR and radio regions. The utilisation of these facilities, as well as data from international facilities, has enabled significant research in the areas of exoplanets, stellar abundances, star formation in the Milky Way and other galaxies, star clusters, pulsars and compact objects, active galactic nuclei, structure and evolution of galaxies, clusters of galaxies, activity in stars and galaxies and transients such as novae, supernovae, gamma-ray burst sources and gravitational wave sources.

Decadal Vision Documents are very important for a community to identify thrust areas and define priorities to make progress in science in a focused manner. Different international communities periodically engage in such exercises. In the year 2004, the Indian Academy of Sciences brought out a Vision Document for Indian Astronomy & Astrophysics[1]. It is indeed very gratifying to see several important recommendations mentioned there (like detection of gravitational waves and making multi-wavelength astronomy a niche area) are well achieved and the various, then proposed, facilities (such as AstroSat, a 4-m class optical telescope, enhancing the wide band capabilities of GMRT and participating in large international telescope projects) are now a reality.

This document provides the Science Vision for Astronomy & Astrophysics over the next decade and a half where Indian astronomers are expected to be part of most of the large international facilities. Providing a pedagogical overview of the ongoing research from the largest to the smallest scales probed, Section 2 summarises the important questions that Indian researchers wish to answer over this period. Section 3 focuses on the status of efforts globally to answer these questions. This section also summarises various observing facilities and surveys that have played a major role in the past decade. Various large facilities under construction and proposed by the international community for the next decade are also listed. A brief review of the status of R&D in our country is provided in Section 4, including science highlights during the past few decades and details of various existing astronomy facilities. Section 5 lists the details of international mega-science projects in which India is already a partner, international mega science projects with Indian contribution and national projects (both ground and space based) that are in various stages of planning.

[1] https://www.ias.ac.in/public/Resources/Other Publications/Overview/astrophys.pdf

This section also provides timeline for various projects and a category-wise priority of projects based on our current and future goals and requirements. In Section 6 we provide some recommendations for funding, management and evaluation of the mega science projects. Section 7 summarises industry-academia interaction. Section 8 focuses on the outlook for the growth of the community. This section provides growth curves of research publication, student intake for PhD, usage of existing facilities, spread of A&A curriculum in higher educational institutions, etc. Section 9 highlights the possible synergy with mega science projects in other disciplines. Finally, in Section 10, the document provides a set of recommendations that we expect will provide the needed platforms to bring the vision to a reality.

2 LEADING ASTROPHYSICAL QUESTIONS

The field of Astronomy & Astrophysics is entering a new era of exploration with the large sky survey programmes that will discover new phenomenon, the extremely large optical/IR telescopes that will allow studies of stars and galaxies at the dawn of the Universe, and the study of planets similar to the Earth around other stars, and the giant radio telescopes that will reveal how the early Universe was transformed by the early galaxy formation. The detection of gravitational waves has opened a new window to study the most extreme environments in the Universe. Ever improving computing facilities enable one to have simulations as realistic as possible. The far-reaching new observational data generated will confront theoretical models and simulations and enable an unprecedented understanding of the Universe, as well as test the laws of fundamental physics at different scales and epochs. Identified below are key areas and questions that Indian astronomers propose to address and make significant contributions to the global quest for understanding our Universe.

2.1 Fundamental Physics

Astronomical observations are interpreted in the framework of basic physics, as we understand on Earth, being time and space independent. For example, while we assume all fundamental interactions are universal, some theories (higher dimensional models or cosmological models with quintessence) allow for their space and time-variations. If dimensionless constants (for example, electromagnetic coupling constant) of interactions have time and space variations, they will have a major impact on our understanding of the Universe. Similarly, it is important to test the validity of fundamental theories like general relativity (GR) at different scales under different astrophysical environments. Therefore, it is extremely important to observationally verify (a) whether the fundamental physical interactions are universal, irrespective of time and space, (b) validity of general relativity across all scales of astrophysical interest, (c) whether gravity is a fundamental interaction or an emergent phenomenon, and (d) the physics that dominates the interactions at supranuclear density expected in the centers of the neutral stars in the early Universe.

It is now well established from a wide range of astronomical observations that about 84% of the non-relativistic matter in the Universe is dark, i.e., it has very weak and as yet undetected interactions with photons and fermions of the Standard Model. Most of the evidences point to the “dark matter” being composed of new fundamental particles beyond the Standard Model of Particle Physics. On the other hand, the observed accelerated expansion of the Universe today indicates the presence of a new exotic form of matter/energy in the Universe with negative pressure (referred to as “dark energy”). Understanding “dark matter” and “dark energy” and any possible interplay between them is very important to understand our Universe and the formation and evolution of large scale structure probed by different observational probes. Therefore, it is of utmost importance to know the constitution of both dark matter and dark energy, the self-interaction cross-section of dark matter, and the origin of matter-antimatter asymmetry of the Universe. To understand these aspects, it might become important to explore the need for a change in the physical concepts as we understand today [like MOdified Newtonian Dynamics (MOND)].

2.2 Early Universe and Cosmology

In the “Big Bang” model, the Universe originated in a singularity. It went through an initial exponentially expanding phase (called “inflation”) that explains why the Universe is homogeneous and isotropic and explains presence of perturbations at very large scales. The earliest observable Universe (using the thermal fluctuations in the Cosmic Microwave Background Radiation, CMBR) is homogeneous and isotropic with very tiny fluctuations (i.e., weaker than 1 part in 10^5). However, the present-day Universe is inhomogeneous and filled with highly complex structures (filaments, sheets, clusters and voids) with large variations in density at smaller scales (i.e < 300 million light-year). Understanding how these structures form and evolve from the initial tiny fluctuations to what we see today is the big challenge facing the cosmology community. While the inflationary scenario does provide the tiny initial density and velocity fluctuations from which the galaxies, clusters, voids and the grand cosmic web that we observe originated, there is much more to be explored and explained.

Due to cosmic expansion (Hubble flow), photons from distant objects are redshifted with respect to the emitted wavelengths. Thus, by measuring the shifts in the wavelength of spectral lines we are able to estimate distances of very far away objects. This, coupled with the finite light travel time allows us to directly observe the evolution of the Universe from very early stages. While we have been developing a consistent sequence of events that has led to the present-day Universe starting from moments after Big Bang, precision measurements are needed to lift the degeneracy in our understanding. There are important questions in this framework that remain unsolved and the questions that we seek answers for are: What were the initial conditions for our Universe and how did they originate? Is the Universe statistically isotropic and homogeneous? What is the large scale topology of the Universe? What is the origin and evolution of cosmic magnetism? Can one measure the mass of neutrinos from their imprint on the large scale structures? How and when did the first sets of stars and galaxies form? What physics governs the formation and evolution of stars from primordial gas? When and how did the Universe get reionised and what is the nature of the dominant sources of reionising radiation? How and when did the first generation of supermassive black holes (SMBH) form? At what stage, and how is the connection between SMBH and host galaxy properties established?

2.3 Galaxy Formation and Large Scale Structure

While the dynamics of the Universe is governed by the "dark matter" and "dark energy", observationally, we use galaxies as the tracers of the matter distribution in our Universe. Galaxies are formed in gravitational potentials of halos of dark matter particles. The star formation in galaxies are related to the efficiencies of gas cooling, fragmentation and subsequent gravitational collapse. They are also influenced by various feedback processes related to gas flows, turbulence, shocks, cosmic rays and magnetic field. It is now well established that in addition to stars, galaxies have gas in the regions between stars (interstellar medium, ISM) and in the circumgalactic medium (CGM, an extended region in a galaxy far beyond the region occupied by stars). Thus, the evolution of galaxies is governed by the evolution of all its constituents like stars, CGM and ISM and the interactions between them. It is also now well established that most of the baryons (normal matter which constitutes material around us) produced in the Big Bang reside in regions between galaxies (i.e so called intergalactic medium, IGM) in the early Universe. However, in the present-day Universe a substantial fraction of these baryons are incorporated into galaxies and clusters of galaxies. Thus, understanding the flow of matter at different scales and processes guiding this flow are essential to our understanding of formation and evolution of large scale structure in our Universe.

Specifically, one would like answers to the following questions using deep observations. How do galaxies form and evolve across the cosmic time? What is the connection between stars, gas and the underlying dark matter distribution? What triggers the formation of the quasar (or active galactic nuclei, AGN) phase in a galaxy and what controls its duty cycle? How large-scale flows and AGN feedback influence star formation and evolution of galaxies? How do interactions of galaxies influence star formation? What are the processes responsible for quenching of star formation in galaxies? What is the influence of large-scale environment on galaxy properties? How different constituents of multi-phase interstellar medium (gas, dust, ionizing radiation field, magnetic field, cosmic rays and turbulence) evolve with cosmic time? What is the origin of multi-phased circumgalactic medium and what drives its time evolution? What is the origin and evolution of thermal state and metal content of the intergalactic medium? Can we account for all the metals and baryons produced in the Universe? Formation and evolution of galaxy groups and clusters? How does the large-scale structure of the Universe defined by gas and galaxies evolve? How important are large-scale filaments in the evolution of galaxies? How well does the large-scale distribution defined by galaxies trace the underlying dark matter distribution?

2.4 Nearby Galaxies

High spatial resolution studies of nearby galaxies (the low-mass end in particular) not only allow one to understand the local Universe in detail but also provide important insights into the nature of dark matter, cosmic reionization and galaxy formation across cosmic time. Systematic mapping of line of sight and transverse velocities of stars and spatially resolved gas kinematics in nearby dwarf galaxies allow us to directly probe the scales where dark matter interactions may play an important role. Spatially resolved measurements of star formation, stellar mass, chemical abundance pattern, distribution of supernova remnants and stellar and gas kinematics will have important implications on the star formation history of these galaxies. This information is very important for our understanding of galaxies in the distant Universe that have similar mass and chemical enrichment. Similarly, it is important to measure the mass of central black holes in active and normal galaxies using stellar kinematics and other probes. Binary neutron stars and binary black holes in the nearby galaxies are the main sources of gravitational waves (GW) that can be detected with the present-day GW detectors. Therefore, a complete accounting of different kinds of binaries in the local galaxies is also crucial. Important questions that remain to be addressed are: What is the density profile of dark matter halos in nearby dwarf galaxies? What are the abundance pattern and spatial distribution of satellite galaxies? What is the amplitude of dark matter density fluctuations at sub-galactic scales? What is the distribution function of SMBH in the local Universe? What kind of stellar populations dominate the low mass metal poor galaxies? Are there dwarf galaxies devoid of any dark matter? What are the physical processes that lead to the dissociation of a dwarf galaxy from dark matter?

2.5 The Milky Way Galaxy

Studies of our Milky Way (MW) Galaxy provides us with a close-up view of the interplay between cosmology, dark matter, galaxy formation and formation of stars and planets. The ongoing, planned and proposed astrometric, spectroscopic and photometric surveys will enable measuring three-dimensional positions and velocities, and chemical abundances for stars in the Galaxy as well as the galaxies in the Local group, leading to a multidimensional view of our Galaxy.

A systematic study of stellar motions and the composition of stars reveals the origin and evolution of the Milky Way Galaxy and its present structure. The Galaxy is broadly composed of three major components: disc, bulge and the halo. Stars are grouped into components based on their kinematic properties (U, V and W) and chemical composition. Apart from the three major components, the Milky Way Galaxy is found to have many more small components in agreement with ΛCDM model which predicts hierarchical formation of the Galaxy due to mergers. Wide-field imaging surveys have discovered several streams, and more such streams are expected to be discovered with the LSST. Stellar streams provide a snapshot of Milky Way stellar halo formation and improve our understanding of its fundamental building blocks. To piece together the puzzle of the Galactic structure and how it evolved is one of the fundamental questions in astronomy. In addition, what is the shape of dark matter potential of the Milky Way? What is the origin and nature of high velocity clouds (HVCs) in the Milky Way and local galaxies? How many satellite galaxies are there in the Milky Way, and what are their star formation and chemical enrichment histories? These are other unanswered questions that can be addressed through detailed observational data as well as theory and simulations.

The Galactic centre presents a unique opportunity to study supermassive black holes in the centres of galaxies and their roles in the formation and evolution of galaxies. High angular resolution observations with the 10-meter class telescopes in the past couple of decades, in the infrared, using adaptive optics and interferometric techniques, have enabled accurate determination of the proper motion of stars within 0.04 pc of Sgr A* (associated with the Galactic centre), and provided the first test of General Relativity around a supermassive black hole. The first ever image of the central black hole Sgr A* in the millimeter by the Event Horizon Telescope provides new insights into accretion, outflow, and gravitational physics at unprecedented scales. Facilities of the future, such as the extremely large telescopes (EELT, TMT, GMT) will enable observations with higher spatial resolutions than currently possible that will enable detection and mapping of the orbits of stars much closer to the centre (Sgr A*), and much fainter. Measurements of the orbits of stars closer to the centre will enable measurement of the precession of the periapse and test the specific metric form of General Relativity, probe the distribution of dark stellar remnants and dark matter around black hole and test the models of galaxy evolution and dynamics. Such observations will supplement theoretical studies and provide a great fillip to black hole science.

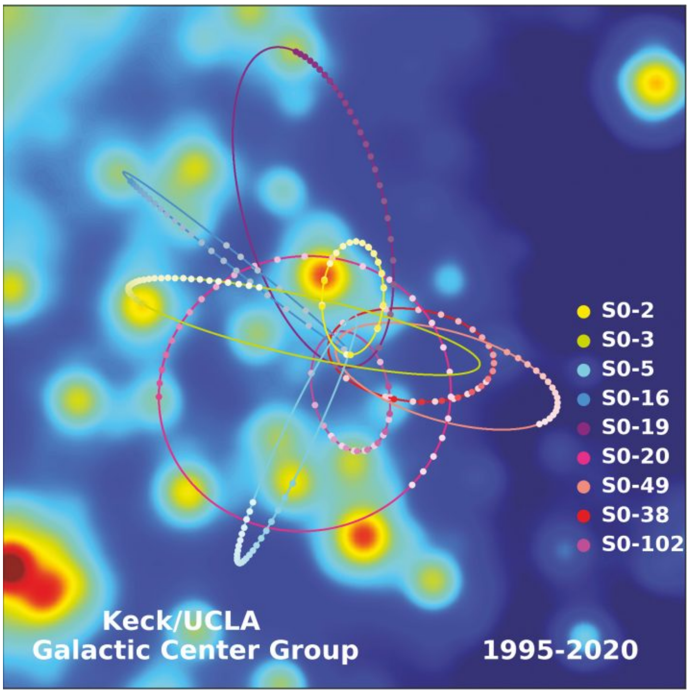

Figure 1: *The orbit of stars within the central 1.0 X 1.0 arcsec region of the Milky Way Galaxy. (Figure credit: UCLA Galactic Center Group - W.M. Keck Observatory Laser Team)*

The infrared observations have also shown the presence of stellar populations that are not easily explained by our current understanding of star formation in a black hole environment. Such high angular resolution observations have led to several questions such as what is the origin of the nuclear massive young star clusters and why is there a dearth of old red giants around the central supermassive black hole?

2.6 The Interstellar Medium and Star Formation

Star (or stellar system) formation and the interstellar medium are intricately related. The interplay between the two is central to fundamental issues of evolution of the Universe at one end and formation of planetary systems at the other, thus influencing virtually every theoretical and observational sub-field. While stellar astrophysics has entered a new era of exploration, a comprehensive picture of the star formation processes and the diverse conditions in the ISM is still elusive. The formation mechanisms of the two ends of the mass regime (the high-mass stars and the self-gravitating sub-stellar mass objects) remain poorly understood both theoretically and observationally. In a broader sense, the presence of dense molecular phase in the ISM is an important ingredient for star formation. On the other hand, the physical state of different phases of the ISM, including the dense molecular phase, is governed by the past and ongoing stellar activities.

It is interesting to note that the metal enrichment of the ISM depends on the integrated star formation history of the host galaxy. Thus, detailed studies of star formation and the physical conditions prevailing in different phases of the ISM are complementary to one another. There are a number of outstanding questions in this field that motivate researchers around the globe. A few are mentioned here. What is the detailed astro-chemistry, the origin of cosmic rays and their influence on the physical conditions in the ISM? Stars are born within molecular clouds, a process that begins almost as soon as the natal molecular gas has itself formed. This fundamental process of formation of the molecular clouds, which is the rate-determining step for star formation itself is yet to be observed. What are the mechanisms that lead to the formation of Giant Molecular Clouds (GMCs)? What is the contribution/interplay of turbulence, magnetic field and gravity in the formation of protostars? The effect of magnetic field on the star formation rate and the stellar initial mass function (IMF) is still an open question. Among the other pertinent questions in the field of star formation that are yet to be fully answered are, the role of jets/outflows in the star formation process, and the viable launching mechanisms of these.

Once the cloud starts collapsing, due to the conservation of the angular momentum, they form accretion discs which have now been observationally confirmed to form as early as the protostar phase. Questions remain on exactly how the angular momentum transport occurs, which lets the infalling gas relinquish its angular momentum to accrete on to the protostar. What are the roles played by the outflows, magnetic fields and various turbulences in the accretion disc? What is the detailed structure of the innermost regions of the disc? Is the accretion episodic for all young stars (like FUors and EXors), or only for a few perturbed systems? The key to understanding this active phase of the protoplanetary disc is via understanding and modelling the complex light curves from YSOs. With the data from modern multi-epoch photometric and spectroscopic time domain astronomy surveys, it will be possible to understand the complex physics of accretion in young stellar objects. What are the processes involved in filtering the chemistry-driving UV radiation incident on the disc that alter the composition of forming planetary systems?

Understanding the various feedback manifestations and mechanisms of high-mass stars is an upcoming field. The strong UV radiation field of the high-mass stars affect the ISM both physically, chemically and mechanically. Easily detectable in high-redshift galaxies, the UV-irradiated gas is an important tool for understanding the history of formation and evolution of structure in the Universe as well. Another realm of feedback from massive young stellar objects involves protostellar jet interaction with the ISM leading to particle acceleration and non-thermal radiation. This opens up a new window to investigate shock physics in stellar systems and contribution to the production of Galactic cosmic rays. The Central Molecular Zone (CMZ) provides an ideal laboratory for probing star formation processes under extreme conditions. The lack of (or inefficient) present-day star formation in the CMZ is surprising given its dense gas reservoir. Despite various proposed theoretical models, the star formation in the CMZ is not well characterized observationally. When we consider the IMF, a number of interesting unresolved aspects remain. A robust observational finding is its near-universality in the Milky Way and neighbouring galaxies. But is it possible to reconcile extragalactic IMF variations with a universal Milky Way IMF? How does it depend on the environment, on metallicity? How does it behave in extreme environments like the Galactic centre? These are some of the yet unanswered questions.

2.7 Cosmic Chemistry

Big Bang nucleosynthesis in the first few minutes of the Universe is believed to have created Deuterium, the two isotopes of Helium (^{3}He and ^{4}He) and a very small amount of Lithium as well as Beryllium (the so called "primordial composition"). Big Bang also predicts the light element abundance as a function of total baryon produced. Therefore, measuring the light element abundances in pristine environments is important to constrain Big Bang nucleosynthesis. Lithium (Li) with atomic number Z=3 is one of the first three light elements (others are hydrogen and helium) known to have been produced during the early Big Bang nucleosynthesis. Over the course of time, Li content in the physical Universe has increased by about a factor of four which is meager compared to rest of the elements, C, N, O, Fe, Ni. etc., which grew more than a million times, over the lifetime of the Universe. Stars are primary contributors to the significant enhancement of these heavier elements through mass ejections and stellar explosions. Li, however, seems to be an exception. The small increase of Li from its original value at the time of the Big Bang is mostly attributed to high energy cosmic ray bombardment of heavier nuclei like C and O in the interstellar medium, splitting them into smaller atoms like Li. It is known that Li is destroyed at relatively low temperatures ($\sim 2 \times 10^6$ K) inside the stellar interiors. Further, mixing up with outer atmospheres leads to the destruction of initial Li over a star's lifetime. Contrary to this general understanding, a few evolved stars (about one in 100 in our Galaxy) are found to have very high Li content in their atmospheres, in some cases exceeding model predictions by a factor of 100,000. Understanding the Li production in such stars is of great importance in the study of stellar evolution and nucleosynthesis.

Almost all other heavier elements in the periodic table are synthesised in the stellar interiors and envelopes during hydrostatic and explosive burning. Each stellar nucleosynthetic path has a different timescale and produces characteristic elemental abundance patterns. It is believed that the first set of stars formed (called "Population III" stars) had "primordial" composition. Subsequent generation of stars formed from the gas enriched by the previous generation of stars. Therefore, the observed abundance ratios and abundance patterns in a given object depend on the nature and duration of star formation activities in their host galaxies. As stellar lifetime is related to its mass, measuring the photospheric metallicities (or elemental abundances) of stars of different masses (and hence different ages) can be used to map how star formation and chemical enrichment proceeded in our Galaxy and other galaxies. Observations of the spectra of metal-poor stars in the Milky Way are the only available diagnostics for studying the nucleosynthesis in the early Galaxy, including the very first stars. These stars preserve the chemical fingerprint of the nucleosynthesis events that occurred before these stars formed. Although detailed spectroscopic observations of the chemical evolution of our Galaxy constitute a major accomplishment in the field, there still are ambiguities due to the lack of isotopic information, particularly those of the heavy elements. Observations of isotopic abundances are therefore extremely important.

The interesting open questions that one seeks to answer are: what is the Deuterium abundance in the metal poor gas, what are Li abundance and Li isotope ratios in metal-poor stars, and what are the sites of Li production in stars with Li enhancement? An accurate measurement of isotopic ratios of heavy elements in stars are important to understand their implications on the chemical evolution of the Galaxy. What drives the abundance pattern of the very metal poor stars, and what is the abundance pattern of metal poor galaxies are the other interesting, but poorly understood questions.

2.8 Compact Objects and Black Holes

The remnants at the end of stellar life such as white dwarfs, neutron stars, and black holes as well as super-massive black holes located at the center of galaxies are usually referred to as “compact objects”. They tend to attract and eventually swallow matter from their surroundings or a binary companion, if present. The surrounding matter plunges toward the compact object due to their strong gravitational force in the form of a planar disk, termed accretion disk. A fraction of the accreted matter forms an outflow which may be in the form of a wind or a highly collimated powerful jet of magnetized plasma moving at speed close to the speed of light in a direction perpendicular to the plane of accretion. Properties of the compact objects along with the inflow and outflow near them are probed using X-rays, γ-rays, and radio waves. Due to their strong gravitational field, they are the best laboratories to test the predictions of General Relativity. Probing their properties, e.g., equation of state of the matter inside a neutron star, accreted material very close to a black hole, or relativistic particles in powerful jets, can help us understand the physics of matter in environments that are difficult or impossible to produce in the lab, and hence may lead to the discovery of new physics or confirm existing complex theories.

After painstaking efforts for decades, scientists have finally been able to detect gravitational waves from cosmic sources since 2015. As of now, the detected sources are black holes and neutron stars in binary systems a few seconds before they merge with each other producing powerful gravitational waves. This new window provides us an important tool to probe compact object binaries in a way that is not dependent on the electromagnetic signal such as X-rays emitted by them. It is expected that as the gravitational wave detectors becomes increasingly sensitive, many more sources will be detected and that will provide an opportunity to probe the physics of these systems with more details through this unique window.

Some important aspects one would like to probe are: strong field tests of gravity using pulsars and black holes; understand the nature of inflow (accretion) and outflow (jets, wind) associated with compact objects; the origin of intermediate mass black holes (IMBH); understanding strong gravity, superdense matter and accretion-ejection mechanism of and around black holes and neutron stars; physics and evolution of millisecond pulsars and their binary system and explanation of the observed parameters; study of continuous gravitational waves from the ellipticity of neutron stars (from future observations with an advanced version of LIGO, and future observatories such as Cosmic Explorer and Einstein Telescope) and orbital rotation of compact binaries (future observations with LISA); multi-messenger observations of neutron star mergers and; search of gravitationally lensed gravity wave signal.

2.9 Transients and Time-domain Multi-messenger Astronomy

A sizable information about our understanding of the Universe is associated with multi-wavelength observations of different types of astrophysical transients. For example, observations of supernovae (SNe), gamma-ray bursts (GRBs) and Cepheid variables are essential to build the so called "distance ladder" and in turn helpful towards constraining observational cosmology. Studies of transients of various categories are required to understand extreme physics, nucleosynthesis of heavy elements, nature of relativistic shocks, particle accelerations, cosmic-ray production, effects of gravity etc. Recent advancements in observational facilities beyond the electromagnetic spectrum have enabled to generalize the area covering a variety of new astrophysical sources at diverse time scales including interstellar asteroids and comets, exoplanets, accreting black holes, merging compact objects etc. This larger scope along with an increased use of sophisticated software, computation tools and astronomical instrumentation using cutting edge technology have opened a new window to understand transients even beyond electromagnetic spectrum in a much broader perspective i.e. multi-messenger, in terms of resolving many open questions in the field of A& A.

Over the last century, systematic searches have led to discoveries of transients from a few to thousands in number. Recent, automated survey programmes have led to the discovery of new types of transients such as the fast blue optical transients (FBOTs) and fast radio bursts (FRBs). Large scale surveys in the coming decade are expected to increase these discoveries by a factor of more than 100, and also to discover a number of unknown types of transients as we start probing the yet unexplored parts of the parameter space described by wavelength, flux, change in flux and time. Recent history has also shown that some of the most interesting and often unexpected breakthroughs come from these discoveries, especially when the large scale surveys are combined with good follow up and monitoring capabilities.

Transients that are a result of explosive events related to the end points of stellar evolution produce essentially all of the heavy elements in the Universe, thus influencing the chemical evolution of a galaxy, star formation and the origin of life. Energetic transients like core-collapse SNe lead to the formation of compact objects like neutron star or black hole. The most extreme stellar explosions like different types of GRBs and their association with very energetic supernovae have a great potential to decipher the underlying extreme physics. Electromagnetic observations of these transients not only probe the newly synthesised elements and their distribution in the ejecta, but also place strong constraints on the explosion mechanisms and environments. Compact binary interactions such as mergers of neutron stars, or white dwarfs also lead to explosive events and observational evidences indicate towards their association with GRBs, SNe and gravitational wave (GW) events. Detailed theoretical modeling and numerical simulations along with enormous amount of multi-wavelength observational evidences have opened a new window for such time-critical transients to be studied in a more systematic way.

Some of the unresolved questions are: what kind of progenitors are responsible to produce thermonuclear supernovae (SNe Ia) - does a white dwarf explode due to a merger with another white dwarf, or due to accretion from a non-degenerate companion? Are some classes of recurrent novae single-degenerate progenitors of SNe Ia? In the case of core-collapse SNe the dominant mechanisms responsible for the removal of the outer layers of the progenitors are still very unclear as well as the understanding of how ubiquitous the presence of a circumstellar matter around supernovae is. Also, understanding which stars explode as supernovae leaving behind a neutron star remnant and which stars collapse forming black holes remains a fundamental astrophysical problem. The prompt emission mechanism and the role of magnetic fields in jet formation, energy dissipation and shock acceleration in GRBs are still not clearly understood. The connection between long GRBs and super-luminous SNe is still poorly understood, leading to questions as to whether the distribution of massive stars in the local universe can be scaled to the very high red shifts to explain the progenitors of long duration GRBs at these red shifts. Also of importance will be the use of the long duration GRBs as standardisable candles in cosmic distance estimation. With the help of upcoming facilities, understanding the demographics of compact binary mergers/short-duration GRBs to probe the nature of the electromagnetic counterpart of the GW sources in more detail and understanding the synthesis of r-process elements in the nearby Universe will be a major aspect of transients studies.

Over the past decade, wide-area optical surveys have discovered a population of transients with fast rise times (of the order of 1-7 days), fast decay times (1/2 peak magnitude in 3-12 days), over a range of peak optical luminosities. These are sometimes called "Rapidly Evolving Transients" (RETs), or "Fast-Evolving Luminous Transients" (FELTs) or "Fast Blue Optical Transients" (FBOTs). So far, very few such objects have been studied in detail. The intrinsic rarity and fleeting nature of these events have made it difficult to identify additional examples early enough to acquire the observations necessary to constrain their nature. Similar to the fast optical transients, in the radio region, "Fast Radio Burst" (FRB) events have been detected with transient radio pulse of length ranging from a fraction of a millisecond to a few milliseconds, caused by some high-energy astrophysical process not yet well understood. The confirmed association of at least one FRB with a flare from a soft gamma-ray repeater suggests at least some of them are associated with very high magnetic field neutron stars. It is also observed that some of the super-luminous SNe are also powered by magnetars. In general, most FRBs are seemingly single flashes. However, some FRBs emit multiple bursts. Thus, the question of what causes FRBs, whether all FRBs can repeat, and whether repeating and non-repeating FRBs arise from different astrophysical channels remain unanswered. Understanding the nature of these fast transients and their progenitors will gain importance with more such events being discovered in the future.

With the given advancement of technology, transients are expected to be explored in detail to not only know more about stellar deaths, mergers of compact binaries, nucleosynthesis of heavy elements and cosmic-ray production, but also to understand the nature of dark matter, dark energy and the initial mass function of the first stars.

2.10 Exoplanetary Science

The 1995 discovery of a Jovian companion to the star 51 Pegasi marked the beginning of a new era in modern astronomy where speculations were laid to rest with the first detection of an extrasolar planet. With the advancement of technology, novel techniques like radial velocity measurements, transit photometry, astrometry, gravitational microlensing, direct imaging, pulsar timing method have now led to the discovery of over 5000 planets and the number is ever increasing. The field of exoplanetary science is focused towards three broad regimes of demographics, atmospheric characterization, and search for habitable planets. The architecture and demographics of the detected population throw open several questions – is the solar system unique? How do we explain the significant fraction of hot-Jupiters and the relatively close-in, super-Earths and/or sub-Neptunes which have no solar system analogs? Further, though some studies have shown possible evidence of universality of planet/star mass ratio, determining whether this or only the planetary mass defines the observed demographics in all mass regimes is crucial to understanding the formation and evolution of planetary systems.

The interlink between the architecture of planetary systems and the host star properties is yet to be firmly established.

For instance, the dependence on stellar age, effect of detailed abundances, metallicity threshold for efficiency of formation, are important areas that are less explored. The mass functions, orbital eccentricity, and metallicity of giant planets strongly suggest multiple formation channels which need confirmation with the growing database. The need of the hour is to resolve intrinsic biases and sensitivities of different techniques that have made it very challenging to combine demographics over a large parameter space.

The driving force behind exoplanetary research is the search for habitable planets beyond the solar system. From the scientific perspective, conditions of habitability depend on intrinsic planetary characteristics, the external space environment governed by the stellar host, their interactions and coupled evolution. Short term fluctuations in stellar activity due to flares and mass ejections produce intense high energy radiation and energetic particles which perturb planetary atmospheres. Slower, long-term evolution of stellar winds influence planetary atmospheres and play a role in their evolution, phenomena which are governed by the presence, or lack of planetary magnetospheres. It has come to be recognized in recent times that these aspects of star-planet interactions play a critical role, along with intrinsic evolution, in determining exoplanetary habitability. Therefore, characterizing host star activity levels, searching for detectable signatures of star planet interactions and presence or absence of magnetospheres in exoworlds, either through stellar monitoring programmes, transit spectroscopy of exoplanets, auroral radio emission or other means has become an area of immense topical interest.

Recent observations have shown beyond doubt that the grain growths in protoplanetary discs starts early, and they even have significant structures in the dust distributions observable with sub-mm interferometry. Are these structures indicators of successful fast planet formation? While we have a good understanding of forming centimeter sized pebbles from grains, the method of growing the larger sized planetesimals out of pebbles is still not fully understood. What are the mechanisms by which planetesimals are grown into full scale planets and can they explain the exoplanet demographics currently observed around our nearby stars, are still all open questions. The thermal and chemical environments in protoplanetary discs and how they evolve over time to influence the planet formation is also something that is not fully understood. This is important to explain the volatile and non-volatile elemental abundance gradients we see in our own solar system as well as in other exoplanets.

The field of exoplanetary science has also entered the era of detailed atmospheric characterization. The spectra of planetary atmospheres reveal not only their physical and chemical properties, but also unravels crucial information about the various atmospheric processes. One of the most fundamental scientific advancements in the next decade is the detailed comparative exoplanetology of hundreds of exoplanets using transit spectroscopy, direct imaging, and high-resolution Doppler spectroscopy. Elemental abundances of exoplanetary atmospheres is essential to understand the formation, evolution and migration scenarios. The origin of hot-Jupiters, that have been in the limelight since the last 25 years, is hypothesized to be either in situ formation or migration to the current location. Migration can occur either through interaction with the protoplanetary disk during their formation or by 'disk-free' mechanisms such as gravitational interactions with a third body. The observed spin-orbit misalignment in such systems may hint at a disk-free migration but migration can also happen through misaligned disks. Recent theoretical studies suggest that chemical abundances could provide new constraints on the mode of migration thus highlighting the need for detailed atmospheric characterization. Exoplanet detection surveys have revealed the high occurrence rate of rocky exoplanets in the solar neighbourhood with a dozen in their habitable zones. The goal is to detect biosignatures in this population with the low-mass stellar hosts being the best suited. Defining a robust biosignature is theoretically challenging but several molecules have been proposed. With the upcoming missions, facilities on the horizon, this may just be round the corner. The field of exoplanetary science is entering a golden era.

2.11 The Sun

The Sun is a variable star with its magnetic activity driving its radiative, electromagnetic and particulate variability – which have profound influence on our space environment and atmosphere. Solar magnetic fields are produced in its interior by a magnetohydrodynamic dynamo mechanism and emerge on the surface of the Sun (photosphere) as sunspots. The emergence and evolution of these magnetic fields on the Sun's surface driven by solar surface plasma flows drive the restructuring of the magnetic fields in the Sun's outer atmospheres – the chromosphere, transition region and corona. Processes such as magnetic reconnection and instabilities in the coronal magnetic fields generate highly energetic solar magnetic storms such as solar flares and Coronal Mass Ejections (CMEs), which are accompanied by intense high energy radiation, solar energetic particle events and eruptions of vast amounts of magnetized plasma material. However, the generation of the large- and small-scale solar magnetic fields and their emergence and evolution in the solar atmosphere is still poorly understood. The role of magnetic reconnection, waves and instabilities in the generation of solar storms such as flares and CMEs is another area of intense study using both observations and theoretical models and simulations. The energetics and dynamics that sustains the million degree hot, solar outer atmosphere – the corona is yet another key question that remains to be understood.

The variable solar activity controls the space environment of solar system planets. The Sun-Earth system is an excellent domain to understand fundamental plasma physics processes in the Universe. Given its profound impacts on satellite and planetary technologies, understanding solar activity leads to applications and space weather forecasting capabilities which are of direct benefit to humanity. In the context of solar activity and its influence on planet Earth, some key problems are (a) understanding the drivers of solar radiative variability which impacts climate,

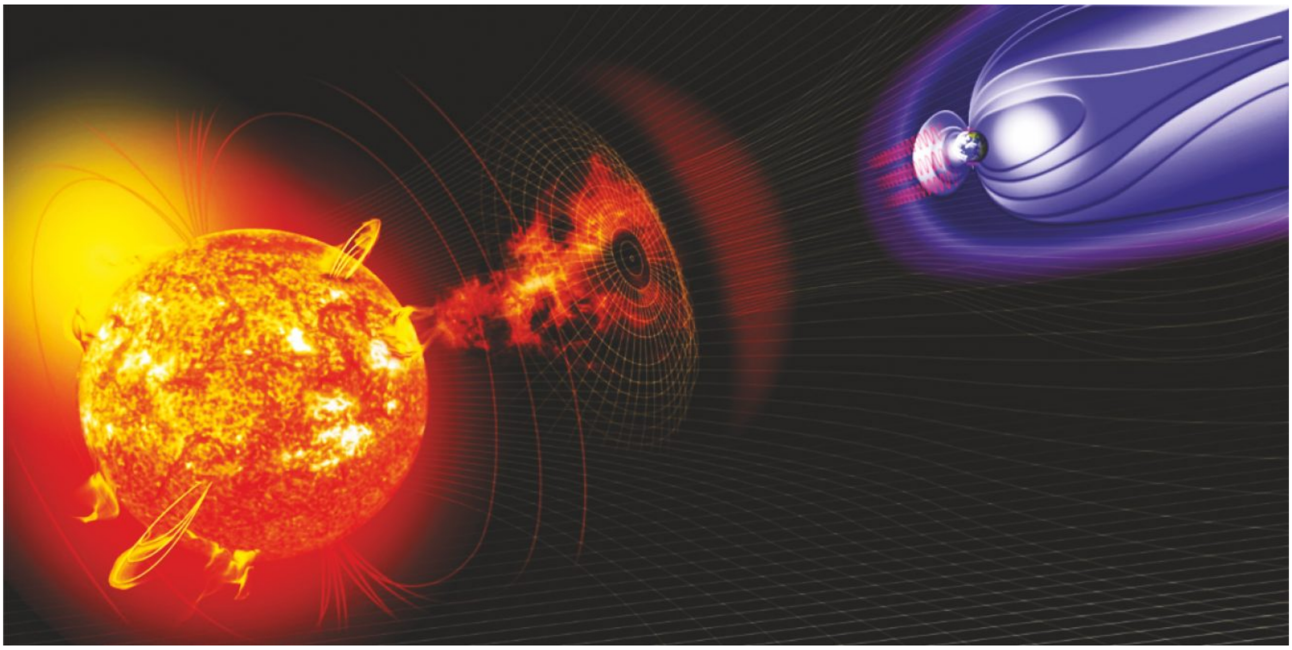

Figure 2: *A depiction of the heliosphere, the connection between the Sun and the planets.*

(b) identification of the processes that accelerate the solar wind, (c) impact of solar activity on Earth's atmosphere and (d) space weather predictions using solar observations and data driven models.

2.12 Solar System Objects

The study of planetary atmospheres is an extremely important aspect of the study of solar system objects. These include the study of the composition and structure of the atmospheres. Of particular interest are (a) study of the composition for bio-signatures, (b) study of changes in the planetary atmospheres over various timescales of minutes to years.

Comets and asteroids provide vital clues to the formation, evolution and the dynamic environment of our solar system. Observations of these objects help in constraining the dynamical, collisional, thermal and compositional evolution and mixing in our solar system. Such studies provide the much-needed comparison for exoplanetary systems.

It is predicted that there are several interstellar objects of extra-solar origin that pass the Earth's orbit. The first such object was discovered in 2017 and named 'Oumuamua'. A comet of interstellar origin, 2I/Borisov, was the second such object discovered in 2019. It is of great interest to understand the trajectory of such objects that will enable tracing their origin. Also of interest is the composition and morphology of these objects.

Near-Earth Objects, or NEOs, are asteroids and comets that pass close to the Earth, within 0.3 AU of the Earth's orbit. These objects present potential threats to our planet. It is of immense importance to survey the sky for the detection of such potentially hazardous objects and determine their trajectory and orbit. Characterisation of the colour, spectrum, light curve and rotation of these objects will enable determining their origin.

3 STATUS OF GLOBAL R&D EFFORTS

The major science questions discussed in the previous section cover a wide range of scales (from the Sun to the entire universe). Several of these questions can, in practice, be addressed by a single observing facility with a suite of instruments. However, there are questions and aspects of a given science question that require using several facilities that enable observations of a class of objects at both the brighter and fainter ends and/or will provide a multi-wavelength perspective. Additionally, there are scientific questions that require large observing time, that are carried out using (i) dedicated survey facilities, (ii) "large observing programmes" with several tens of observing nights dedicated for a specific project proposed by a large community and (iii) network of observatories operating at different wavebands located in different part of the world and in space. The efforts of the global Astronomy & Astrophysics community in addressing some of the scientific questions listed in the previous section using existing and future large facilities and surveys in different wave bands are summarised in this Section.

3.1 UV-Optical-IR

3.1.1 Ground Based Facilities

Any scientific question that requires optical and near-IR observations of faint and/or distant targets are at present addressed using ground based 8 to 10-meter class telescopes operating in the optical (0.4 -1.0μm) and near-IR ranges (i.e. 1-2μm). There are fifteen 10-meter class telescopes in the world, with capabilities to perform deep imaging, high resolution and/or multi-object spectroscopy in the optical and near-IR ranges, operational today. Few of them also possess capability to produce sharp images negating the effect of atmospheric blurring effects (using the "adaptive optics" technique). Some of the main accomplishments of these telescopes are summarized below.

- By determining the wavelengths of relevant spectral lines, the best possible constraints (one part per million) on the time variation of electromagnetic coupling constant (α) and electron-to-proton mass ratio (μ) are obtained. *However, one needs an order of magnitude improvement in the sensitivity to be able to challenge the limits set by atomic clocks on earth.* Astronomers are planning to achieve such a sensitivity using highly stable spectrographs and wavelength calibration using laser frequency combs.

- The 10-meter class telescopes have played a very important role in the field of early Universe and cosmology. Temperature measurements of the cosmic microwave background at different space and time have allowed us to confirm one of the main predictions of the Big Bang models. These telescopes also played an important role in proving the accelerated expansion of the Universe and confirming the Lambda cold dark matter (ΛCDM) paradigm. Measurements of Deuterium abundance and spatial fluctuations of matter in the Universe through spectroscopy of distant objects have allowed constraining the parameters governing the ΛCDM models and the power-spectrum of density fluctuations.

- These telescopes played an important role in constraining the epochs at which Hydrogen and Helium in the Universe were re-ionized. They also helped in detecting the nature of galaxies and the presence of supermassive black holes in the very early Universe. Deep imaging studies have allowed mapping the distribution of galaxies and quasars over cosmic time. Spectroscopic observations of bright distant objects have proved that most of the baryons in the Universe are in the diffuse intergalactic medium and all galaxies are surrounded by the so-called circumgalactic medium. *While these observations have enabled astronomers to build a framework of galaxy formation and evolution, important breakthrough in our understanding will be possible only when detailed spectroscopic studies of the distant faint galaxies are possible. This is at present beyond the capabilities of the existing telescopes.*

- Thanks to these large telescopes it is now possible to measure the rate at which distant galaxies form stars, the total mass contained in the stars and the rate at which gas is ejected from the distant galaxies in the form of winds. However, due to Earth's atmosphere most of the distant galaxies are not spatially resolved by the ground based observations. Measuring the spatial distribution of above mentioned quantities is very important for building a complete understanding of various physical processes associated with star formation in distant galaxies. *Larger facilities with adaptive optics capabilities and integral field spectroscopic techniques will enable achieving the same.*

- Accurate tracking of the motion of stars in the central regions of Milky Way has led to the measurement of the mass of the central black hole. Kinematics of stars is one of the cleaner ways to measure the black hole mass at the center of galaxies. At present this technique is applicable only to our Galaxy. *Extending this to nearby galaxies is important and possible only using larger telescopes (i.e 30-meter class telescopes) with higher spatial resolution imaging capabilities.*

- Observations of distant supernovae have led to the accurate measurement of the Hubble constant and the confirmation of the accelerated expansion of the Universe. Spectroscopic observations of various transients have revealed their chemical composition and related nuclear processes and the nature of the ambient medium as well as that of the intervening objects between us and the transients. Similarly, the 10-meter class telescopes have played a major role in detailed studies of the temporal evolution of the first electromagnetic counterpart of a neutron star-neutron star merger that produced detectable Gravitational Waves. They also played a crucial role in understanding the host galaxies of GRBs and FRBs. *Spectroscopic studies of transients occurring at large red shifts are important to understand the chemical composition and star formation during the early Universe, and this will only be possible with the future, larger telescopes.*

- Precise measurements of radial velocity and transit properties have enabled the detection of over five thousand planets around stars outside of our solar system. It is now possible to characterise the atmospheric properties of some of those exoplanets. *High contrast and high spatial resolution imaging and spectroscopic capabilities are proposed by the international community for pushing this research to the next level.*

It has now been recognized by the international community that to make further progress in the next decade, it is important to build larger aperture telescopes (typically of 20–50-meter diameter). The main aim is to have large collecting area and achieve sharpest possible images (beating the atmospheric blurring) over a wide wavelength range. However, such extremely large telescopes can only be built using large international collaboration. As of now there are three such telescopes being built by the international community: (1) Thirty Meter Telescope (TMT), (2) Giant Magellan Telescope (GMT) and (3) European Large Telescope (ELT). These telescopes will start operation sometime in the next decade and are expected to serve the international community for several decades to come.

Major technological developments that helped the 10-meter class telescopes to achieve their success include: segmented mirror technology, adaptive optics, integral field spectroscopy and optical interferometry. In order for the extremely large telescopes to be successful, it is important to (1) obtain suitable segmented mirror technology to operate a coherent 30-meter aperture, (2) be able to produce sharp images over a large field of view and (3) build highly multiplexed instruments to utilise every photon collected by the telescope. It is expected that, in the era of the extremely large telescopes, the 10-meter class telescopes will play an important role as survey instruments and instruments for follow up studies.

The Indian astronomy community has limited access to the existing 10-meter class telescopes either through competitive international time allocation process or through archival data. This has prevented the Indian community in getting early access to some discovery space. However, this is expected to change in the coming decade as India is now one of the partners of the TMT observatory with ~10% share in the project. Our participation in this project has enabled us to participate in the development of some of the major science projects and technologies (as detailed later in this document). *However, to achieve maximum benefits it is also important for the Indian community to have access to a 10-meter class telescope fitted with a range of state-of-the-art instruments.*

3.1.2 Space Observatories

Hubble Space Telescope: The Hubble Space Telescope (HST) is a 2.4-meter telescope in space performing observations in the far-UV (i.e. ~1200Å) to near-IR (2.2 μm). Despite its small size and in operation for nearly three decades, the HST consistently outperforms many of the most advanced ground-based telescopes (thanks to its high resolution imaging capabilities without being affected by the atmospheric blurring) and is still considered the pinnacle of optical and ultraviolet astronomy, with a heavy demand for its use, greatly exceeding the available observing time each year.

- HST played an important role in measuring the expansion rate (or Hubble constant) of the Universe at an unprecedented 2.2% accuracy. This measured expansion rate corresponds to an age for the Universe of 13.8 billion years. HST observations played an important role in creating a robust "distance ladder" based on nearby parallax, Cepheid variables, and distant supernovae. All these observations led to the discovery of the accelerated expansion of the Universe and the idea of "Dark Energy". Interestingly, the Hubble constant estimates from cosmic microwave background experiments do not agree with those based on HST and other ground based observations. *Resolution of this so called "Hubble-Tension" is an important endeavour in the coming years.*

- Dedicated deep field observations using HST (Hubble Deep Field, Hubble Ultra Deep Field, Hubble Deep UV Legacy Survey and Frontier fields) unveiled the details of the evolving universe, tracked the star formation in galaxies over billions of years, and documented the period over which star formation activity in our Universe had a peak, which was about 3 billion years after the Big Bang. Using the gravitational lensing effects, "the frontier field" observations pushed our ability to detect fainter objects which enabled us to gain insights into the contents of the Universe at farther and farther distances (earlier and earlier in cosmic history). Programmes such as Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS) have allowed one to investigate the distribution and evolution of galaxy morphology, galaxy clustering and mergers in the early Universe. Data collected from these observations are available for public and forms the backbone of most of the ongoing research in the field of galaxy formation in the Universe.

- Hubble's spectroscopic observation of distant UV-bright quasars have been instrumental in (i) constraining the epoch of He^+ reionization (ii) quantifying how baryons are distributed around galaxies, large scale filaments and voids and (iii) constraining the strength and redshift evolution of ultraviolet ionising background.

- The UV and high spatial resolution capabilities of HST have allowed one to track star- and star-cluster-formation and role of dust and gas in numerous nearby galaxies beyond the Local Group. Additional factors such as different types of star clusters, the interstellar medium, and the environments of supernovae are being used to arrive at a more complete picture of the dynamical history of the relatively nearby Universe.

- Precise HST observations of star cluster members in our Galaxy have allowed one to determine their luminosities and temperatures. This has enhanced our understanding of star formation, stellar evolution, and inputs to the theoretical models used to explain these phenomena. These advances are important as similar models are used to understand stellar populations of galaxies by using the observed spectral energy distribution.

- HST also played an important role in the exoplanet (including Earth-like planets) studies. HST took the first visible-light image of an exoplanet beyond the solar system. Transit observations and direct measurements of chemical compositions of planetary atmospheres using HST have allowed us to characterise exoplanets and their atmosphere. Numerous planets with and without hazy atmospheres were found. HST observations have also found organic molecules on an exoplanet.

It is hoped that HST will continue to work in the coming decades. However, no servicing or upgrade missions are planned. The Indian community has been successfully using HST archival data in combination with the ground based observations for their research. Many Indian astronomers have successfully made proposals for observing time on HST and were awarded observation time. *As there are no UV spectroscopic missions planned in the near future, the proposed UV spectroscopic telescope INSIST (Section 5) by the Indian community (ISRO) will play an important role.*

Spitzer Space telescope was an observatory class (like HST) infrared observatory which was in operation during 2003-2020. It was launched with an aim to provide a unique, infrared view of the universe and allow us to peer into regions of space that are hidden from optical telescopes by opaque gas and dust. Spitzer was an 85-cm diameter telescope capable of imaging in the 3.6 - 160 μm and spectroscopy in the 5.2-38 μm wavelength ranges. Spitzer's list of accomplishments includes producing the most extensive map of the Milky Way galaxy; some of the first investigations of exoplanet atmospheres; the detection of seven Earth-size exoplanets around the TRAPPIST-1 star (the most rocky planets ever found around a single star); detection of the earliest-forming galaxies ever studied some of which formed within less than 400 million years after the Big Bang; and the discovery of a new ring around Saturn. All the data obtained with Spitzer are archived and publicly available.

The James Webb Space Telescope (JWST), a joint venture of the three leading space organisations around the world- National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and Canadian Space Agency (CSA) is an observatory class space telescope launched in December 2021. The 6.5-meter diameter of the primary mirror of JWST, composed of 18 hexagonal mirror segments, makes it the largest space telescope ever built. The JWST operates in the wavelength range from visible to mid-infrared (0.6 - 28.3 μm). The unprecedented infrared sensitivity of JWST will play a pivotal role to address some of the outstanding questions in fields of astronomy and cosmology. The three main instruments aboard JWST are NIRCam Near InfraRed Camera), NIRSpec (Near InfraRed Spectrograph), and MIRI (Mid-InfraRed Instrument). The primary science objectives of JWST include understanding the formation and evolution of the first stars and galaxies, birth of stars and planets, and study of bio-signatures in exoplanets.

While India is not a partner in this space telescope project, Indian astronomers will be able to apply for observing time through competitive open proposals.

3.2 Radio

At present, there are many radio telescopes covering different parts of the radio frequency spectrum and different aspects of radio astronomy: large single dish observatories such as Parkes in Australia, Green Bank Telescope (GBT) in USA, Effelsberg in Germany, Sardinia in Italy, and the 500-meter Aperture Spherical Telescope (FAST) in China, as well as array instruments such as the Murchison Widefield Array (MWA) in Australia, LOFAR (Low Frequency Array) in Europe, Ooty radio telescope (ORT) and GMRT in India, MeerKAT in South Africa, VLA (Very Large Array) and LWA (Long Wavelength Array) in USA, CHIME (Canadian Hydrogen Intensity Mapping Experiment) in Canada, ALMA (Atacama Large Millimeter/submillimeter Array) in Chile. Furthermore, there are very long baseline array telescopes – combinations of individual observatories over continental and inter-continental scales that are operated in a coordinated manner to achieve super high resolution for specific studies e.g. the VLBA (Very Large Baseline Array in USA), the European VLBI network (EVN), the East Asian VLBI network, and the Event Horizon Telescope (EHT). This concept has also been extended to use space based radio observatories (e.g. RadioAstron space VLBI mission) working in tandem with the ground based ones to achieve some of the highest spatial resolutions in radio astronomy. This compendium of facilities enables astronomers to obtain a fairly powerful, detailed and comprehensive view of the Universe, especially when used in conjunction with facilities in other parts of the electromagnetic spectrum as well as in other regimes such as gravitational wave astronomy.

In addition, special radio astronomy observatories such as Antarctic Impulsive Transient Antenna (ANITA) and Askaryan Radio Array (ARA) are also being used to observe ultra-high energy neutrinos and cosmic rays. These probe the highest energy phenomena taking place in the Universe and also present an opportunity to study fundamental physics at energies much higher than currently possible in laboratory accelerators.

The above mentioned telescopes are used to study continuum and spectral line emission from distant sources. In particular, radio continuum emission from stars, compact objects, AGN, galaxies, galaxy clusters and transients are regularly used to derive physical conditions in these objects. Spectral line studies (using H I 21-cm line or molecular line) are useful to measure redshift of the sources, place constraints on variation of fundamental constants, and extract physical conditions prevailing in these sources. Observed rotation and dispersion measures, and absorption line signatures are used to study the nature of intervening gas. Some of the above mentioned telescopes have been used to plan strategies and experiments related to the “Epoch Of Reionization”. *Large progress in terms of volume and redshift coverage of these studies is expected with the upcoming facilities that will provide wide area and frequency coverage with enhanced sensitivity.*

There are active plans for building next generation radio astronomy facilities at much larger scales, of which the biggest one is the Square Kilometre Array (SKA) which involves most of the countries active in the field of radio astronomy as partners. The SKA, with completion of Phase-1 slated towards the end of the present decade, is expected to revolutionise our understanding of the Universe in various domains. *The Indian community is part of SKA and will have direct access to the telescope from the very beginning.*

3.3 X-rays and γ-rays

At present, many space-based X-ray and γ-ray observatories are being used to study high energy radiation from astronomical sources. These include: AstroSat, Chandra, XMM-Newton, Swift, Integral, NuSTAR, NICER, Insight-HMXT, eROSITA, IXPE and Fermi. Additionally, there are a few ground-based facilities like the MAGIC Florian Goebel Telescopes, the High Energy Spectroscopic System (H.E.S.S) array and the recently commissioned MACE telescope located at Hanle, that are used to study very high energy (VHE) γ-rays.

The various X-ray and γ-ray telescopes, with their unprecedented sensitivity and angular resolution, have helped astronomers make significant progress in addressing many of the key questions listed in the previous sections, particularly those related to black holes and explosive events. For example, by studying the shock wave associated with supernova explosions, cause and circumstances of the death of the stars have been identified. By mapping the radioactive material in supernova remnants constraints have been put in the theories of the exact mechanism of stellar explosions. X-ray emission from gas particles seconds before they plunge into a black hole may be observed and that provides crucial information about the physical properties of inflow near black holes: black hole spin has been estimated using how strong gravity would affect the emission lines produced by hot gas very close to the black hole. Observations of compact objects in other galaxies have been made, which may potentially be the elusive intermediate mass black holes. The equation of state of neutron star matter has been probed. Collimated jets of magnetized plasma moving at speed close to the speed of light have been observed to extend up to hundreds of thousands of light years from the center of the galaxy. These are ideal laboratories to study acceleration of particles to high energies at a scale which are not possible to be reproduced on the Earth. Our understanding of the formation and evolution of galaxies have been revolutionised by studying the interaction of these powerful outflows with the interstellar and intergalactic medium. It has been discovered that X-ray emitting hot gas surrounding galaxy clusters corresponds to 90% of all atoms in the Universe. In addition, deep X-ray surveys with Chandra and all sky survey with eRosita is leading to the discovery and identification of new AGNs and clusters of galaxies. The IXPE, launched in 2021, is studying X-ray polarisation from a variety of objects. Another X-ray telescope XRISM, with relatively moderate capabilities was recently launched in late 2023.

Several X-ray Astronomy missions are under development or under review for launch in the present or next decade. The major X-ray Astronomy mission approved for development is ESA's ATHENA (Advanced Telescope for High-Energy Astrophysics) mission selected under the Cosmic Vision Program to explore the “Hot and Energetic” Universe. ATHENA will operate in the energy range of 0.2-12 KeV and will offer spectroscopic and imaging capabilities. ATHENA's planned capacities, in particular its energy resolution, are 1-2 orders of magnitude better than those of current facilities. However, it will probably not be launched before 2030. Other proposed missions are the SVOM (France and China) and Thesesus (ESA M5 proposed).

The Compton Spectrometer and Imager (COSI, USA) is a γ-ray telescope expected to be launched by NASA in 2025. It will study the recent history of star birth, star death, and the formation of chemical elements in the Milky Way. There are other γ-ray telescopes proposed like the e-ASTROGAM, that will be very similar to Fermi but with an angular resolution that is 4-6 times better than Fermi, the HERD (China) and the GAMMA-400 (Russia).

3.4 Large Sky Surveys

All sky surveys play an important role in astronomy. They are extremely important to (i) build any unbiased volume limited as well as flux limited samples of different kinds of astronomical sources to quantify their spatial distribution and time evolution, (ii) quantify the time variability properties of different sources, (iii) find unexpected class of objects and (iv) monitor a wide range of variable and transient sources at a higher cadence. Such surveys have helped us constrain cosmological parameters, dark matter distribution in the universe and discover various spectacular transient sources such as peculiar SNe, GRBs, FRBs, FBOTs, tidal disruption events, etc.

3.4.1 Ground Based Surveys

In the past decade the Sloan Digital Sky Survey (SDSS) has made a huge impact in nearly every aspect of astronomy, through regular and highly organised photometric and spectroscopic data releases. Interestingly, the main survey is been carried out using a 2.5-m optical telescope. The large scale structures probed by galaxies and quasars (and IGM absorption detected in their spectra) found by the SDSS survey have provided important constraints on various aspects of the Big Bang model. In particular, detection of Baryonic Acoustic Oscillations (BAO) in the galaxy distribution at low redshift (nearby) and IGM matter distribution at high redshift (distant) are very important results. Thanks to the well organised data archive, SDSS data are used by astronomers around the world to address various scientific questions and also construct unbiased sample for detailed investigations using larger telescopes. Similarly, near-IR all sky data obtained using Two Micron All-Sky Survey (2MASS) and United Kingdom Infra-Red Telescope (UKIRT) Infrared Deep Sky Survey provided useful catalogues of near-IR sources. In the radio, high frequency surveys using Very Large Array: New VLA Sky Survey (NVSS), the Faint Images of Radio Sky at Twenty centimetres (FIRST) and the Very Large Array Sky Survey (VLASS) have played an important role in our understanding of the radio Universe. Low frequency radio surveys such as the TIFR GMRT Sky Survey (TGSS), the GaLactic and Extra-galactic All-Sky MWA survey (GLEAM) and the LOFAR Two-metre Sky Survey (LoTSS) have provided very interesting insights into our understanding of the Universe at low frequencies, and of various relic radio sources.

At present, several optical, near-IR and radio all sky surveys are pursued by the astronomy community with an aim to map large volumes of the Universe at a much higher accuracy than SDSS. These include the Dark Energy Survey (DES), carried out using the 4-m Blanco telescope, its spectroscopic counterpart Dark Energy Spectroscopic Instrument (DESI) survey using the 4-m Mayall telescope in Chile and the Visible IR Survey Telescope for Astronomy (VISTA) using the 4-m ESO telescopes. The Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST), Guo Shoujing Telescope (China) is conducting a wide-field survey, the LAMOST Experiment for

Galactic Understanding and Evolution (LEGUE), consisting of an extra-galactic spectroscopic survey aimed at understanding the large scale structure of the Universe and a stellar spectroscopic survey, including a search for metal-poor stars in the Galactic halo, to provide information on the structure of our Galaxy. Another interesting survey aimed at tracing the history of the Milky Way through stellar spectroscopy is the GALactic Archaeology with HERMES (GALAH) survey using the Anglo-Australian Telescope. *It is desirable that the Indian astronomy community plans to carry out large surveys using our facilities, identifying niche areas where such a survey can make a big scientific impact.*

In the radio, MeerKAT and ASKAP telescopes are carrying out more sensitive surveys in the low frequency ranges. Success of these surveys depend crucially on systematic data releases with uniform quality of the data and available access to these data to a large international community. The GMRT is carrying out the GMRT High Resolution Southern Sky (GHRSS) survey, which is one of the most sensitive mid-frequency surveys for pulsars and FRBs today.

The last decade has also seen several all sky time-domain surveys aimed at scanning the sky more frequently compared to some of the surveys discussed above. The main aim is to detect a wide range of transients and monitor them with a better cadence. Such surveys include: the Catalina Real-time Transient Survey (CRTS), the Palomar Transient Factory (PTF), the Zwicky Transient Facility (ZTF), the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS), the All Sky Automated Survey for SuperNovae (ASAS-SN), etc. These surveys have been very successful in discovering various new kinds of transients. The success of these surveys mainly hinges on the ability to process the data and identify potential transients automatically and disseminate information to the global astronomy community immediately for classification and follow-up observations. This mode of operation has now become the norm of the time-domain astronomy community. This field will have a great boost with the upcoming Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) project using the 8.4-meter, wide field Simonyi telescope. In the radio domain, instruments such as the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and The Hydrogen Epoch of Reionization Array (HERA) play the role of transient detection telescopes. Various international communities and multinational collaborations are planning to set up a network of detectors for follow up observations of transients. *It is desirable that the Indian community participates in such international network(s) through its own network of telescopes.*

3.4.2 All Sky Surveys from Space

Several space telescopes were launched primarily to survey most or all of the sky at different wave bands in the UV-optical-IR range. A few most notable ones are mentioned below.

- **Galaxy evolution explorer (GALEX of NASA)** was operational during 2003-2013. GALEX was used to perform series of all-sky and deep sky imaging surveys in the near and far UV slitless spectroscopic modes. GALEX was designed to measure the history of star formation in the Universe by observing in the ultraviolet wavelengths. The data products are made available in its archives.

- **Wide-field Infrared Survey Explorer (WISE)** was launched in 2007. WISE performed an all-sky imaging survey at 3.4, 4.6, 12 and 22 μm wavelengths, over ten months using a 40-cm diameter infrared telescope. The data products (containing images and catalog of sources detected) are now publicly available. They are being used to study the local Solar System, the Milky Way, and the more distant

Universe in a dust unbiased way.

- **AKARI,** a 68.5-cm telescope, is the first Japanese satellite dedicated to infrared astronomy, with the main objective to perform an all-sky survey with excellent spatial resolution and mapping the entire sky at six infrared bands covering 9 to 180 μm. The data are used to study nearby solar system objects, zodiacal light, brown dwarfs, young stars, debris disks and evolved stars in our Galaxy and in other galaxies of the Local Group.

- **GAIA,** an ongoing mission of the European Space Agency (ESA) has measured distances to an unprecedented number of stars in the Galaxy to a very high accuracy. It improves on the Hipparcos mission by a factor of 200 in position accuracy and a much larger factor in brightness by using a set of techniques and advanced instrumentation and data reduction techniques. GAIA has also measured proper motions of stars and together these measurements allow us to construct the phase space distribution of almost all the stars in the Galaxy.

- **Kepler and K-2,** were NASA's space telescopes that surveyed specific regions of the sky for a combined period of 9 years, and together discovered over around 3200 exoplanets.

- **TESS,** NASA's Transiting Exoplanet Survey Satellite is an ongoing all sky survey mission searching for planets outside of our solar system, including those that could support life. Launched in 2018, the survey has cataloged thousands of planet hosting stars.

- **eROSITA**, a satellite launched in 2019 jointly by the German and Russian Space agencies is carrying out an all sky survey in X-rays (the first since 1990) and mapping the structure of the energetic universe, and the evolution of the thermal structure and chemical enrichment with redshift by discovering hot gas from all massive galaxy clusters in the observable Universe.

- **Euclid,** an ESA medium class astronomy and astrophysics space mission launched in July 2023. This is a 1.2-meter telescope with imaging capabilities in the visible and near-IR wavelength ranges. Slitless spectroscopy is also possible for some bright targets. The main aim of this mission is to understand the nature of dark energy through deep imaging and spectroscopy. In addition, Euclid observations will provide insightful information on initial conditions that seeded the formation of cosmic structures and on the physics of early universe. Euclid will obtain deep images of 15,000 deg^2 of the darkest sky. Three “Euclid Deep Fields” will cover around 40 deg^2 at a greater depth to extend the scientific scope of the mission to the high-redshift universe.

A few dedicated survey missions that are expected to be launched within the next few years are provided below.

- **Nancy Grace Roman Space Telescope** is a planned 2.4-meter NASA observatory designed to address the nature of dark energy and important questions in the field exoplanets, and infrared astrophysics. The telescope will have wide field imager operating the near-IR wavelengths and a Coronagraph. The Wide Field Instrument will measure light from a billion galaxies over the course of the mission lifetime. Wide field images of the of the inner Milky Way will be used to find ~2,600 exoplanets using micro-lensing techniques. The Coronagraph instrument will be used to perform high contrast imaging and spectroscopy of individual nearby exoplanets. The proposed mission lifetime is 5 years, with a potential to extend it by 5 more years.

- **The Space Variable Objects Monitor (SVOM)** is a small X-ray telescope satellite under development by China National Space Administration (CNSA), Chinese Academy of Sciences (CAS) and the French Space Agency (CNES), launched in June 2024. The main scientific aim of this mission is to study the gamma-ray burst events resulting from the explosions of massive stars.

3.4.3 Surveys for Solar System Objects

The Outer Planet Atmospheres Legacy (OPAL) programme using the HST is an example of a long term, deep time survey of the solar system that has established a baseline of consistent data with a yearly cadence since 2014. Similar deep time survey programmes are envisaged with the mega facilities such as the JWST and ELTs in the future. The study of asteroids, comets and atmospheres of planets are some key science programmes of all the future major facilities. The JWST will observe asteroids in the wavelength regions that are not possible from the ground. This will add to our understanding of surface composition, alteration and physical properties of asteroids.

There are a few dedicated surveys conducted by ground-based 1–2-meter class optical telescopes for detection and follow-up of Near-Earth objects (NEOs). While the completeness of these surveys exceeds 90% for NEOs larger than 1 km in effective diameter, the completeness is around 30% for NEOs larger than 140 m, and just around 1% for objects of the size ~20-50m. At present, surveys such as the ZTF survey and international collaborations such as the GROWTH collaboration are concentrating on the smaller sized NEOs. The WISE/NEOWISE mission is probably the only space based telescope involved in NEO survey. Future surveys such as the LSST and NEOCam are expected to increase the completeness factors. LSST will also enable characterisation of these objects. In addition to ground based observations in the optical, telescopes operating in the radio and millimeter wave regions are also proposed to be utilised for survey and studies of NEOs. Such multiwavelength studies are ideal to characterise different populations and also enable more intensive time-resolved follow-up for unresolved objects. Needless to mention that any survey dedicated for the search of NEOs will also enable detection of the interstellar objects.

3.5 CMBR Experiments

The Cosmic Microwave Background Radiation (CMBR) is a nearly isotropic, black-body radiation possessing a temperature of 2.725 K today. The CMB photons arriving at us today from different directions in the sky have travelled unimpeded across the observable universe (13 billion light years) and show tiny variations in temperature (CMB anisotropies) and a net linear polarisation pattern that are imprints of the mildly perturbed early Universe.

Over the past two decades, CMBR observations from space have provided the cleanest and richest source of data for understanding our Universe. Most of the cosmological information in the CMB temperature fluctuations has been harvested by European Space Agency's Planck mission that was launched in 2009, the third generation of the spectacularly successful CMB space missions following COBE DMR (NASA, 1989) and WMAP (NASA, 2001). This has led us to converge on a standard model of cosmology and determine the parameters involved to a high precision. These observations have also provided important constraints on the neutrino mass, electron scattering optical depth, and the nature of dust particles in our Galaxy.

The main goals for the CMBR experiments in the coming decade are: (1) Detection of the signatures of primordial gravitational waves, which, according to the prevalent paradigm of inflation, are expected to have originated in the early universe, leaving imprints as polarisation in the CMB. (2) Accurate measurements of the CMB polarisation. This would also reveal ultra-high energy physics, if inflation operates at the energy scale of 10^{16} GeV (about a trillion times more than that attained in the Large Hadron Collider!) corresponding to Grand Unified Theories and would be the first direct evidence of quantum gravity. Such measurements can also place important constraints on the primordial magnetic fields. (3) Detection of weak gravitational lensing (WL) signal in the CMB polarisation. This would provide a high signal-to-noise map of the integrated matter distribution in the Universe thought to be dominated by dark matter of unknown nature, whose presence is detected only through its gravitational effects. (4) Constraining the total mass of neutrinos, that will permit us to fundamentally establish the neutrino mass hierarchy from astrophysical observations.

Some of the international space experiments in different stages of planning include the Lite satellite for B-mode polarisation and Inflation from cosmic background Radiation Detection (LiteBIRD by JAXA+NASA), the Primordial Inflation Explorer (PIXIE: by NASA) and the Cosmic Origins Explorer (CoRE by ESA). Indian scientists have also proposed a space mission, CMB Bharat, to study the CMBR.

There are also an enormous amount of CMB science that can be done using the ground based detectors. Experiments like the BICEP 3 (Background Imaging of Cosmic Extragalactic Polarization) aim to measure the CMB B-mode polarisation, that is likely to carry the signature of primordial gravitational waves. The primary challenge however is to separate the B-mode caused by the galactic dust from the cosmological signal. To reduce this contamination, the ground based detectors focus on those patches of the sky which are relatively clean from galactic dust. While the space based detectors, being able to probe both small and large angular scales simultaneously may have a better chance of detecting the B-mode, the ground based detectors are quite significantly inexpensive, and hence firmly hold their place.

3.6 Gravitational Wave Observatories

Gravitational waves are emitted when there are sudden changes in the curvature of space-time and these often result from catastrophic events like mergers of compact objects like black holes, neutron stars, or, supernova explosions. Low intensity gravitational waves are also emitted from pulsars and, in principle, signal from these can be added over a long period to improve signal to noise ratio. Lastly, there is interest in detecting the stochastic gravitational background that results from cosmic inflation phase transitions in the early universe, and also from a combination of a very large number of sources of gravitational waves.

After initial attempts to observe gravitational waves with bar detectors in 1960s, focus shifted to L-shaped interferometers. The first generation LIGO (Laser Interferometer Gravitational-wave Observatory) demonstrated the possibility to detect and measure extremely tiny distance fluctuations caused by the passage of gravitational waves. This was followed by the next generation GW LIGO detectors in the USA, VIRGO detector in Europe and the most recent KAGRA detector in Japan. Gradual developments in technology over four decades finally resulted in the first detection of gravitational waves by LIGO in 2015. Then in 2017, the electromagnetic (EM) follow-up of the binary neutron star merger discovered by the network of the LIGO-Virgo detectors, showcased a remarkable international coordination by the global observational astronomy community. In the last six years the LIGO-Virgo observatories have yielded nearly hundred confirmed detections of a variety of merger events involving black holes and neutron stars. Enormous amount of science has resulted from these observations in a short span of time. We learned that there is a large population of heavy black holes in the universe, intermediate mass (more than 100 times the mass of the sun) black holes were discovered; it was firmly established that good fraction of heavy metals like gold in the Universe was created in binary neutron star mergers; equation of state of nuclear matter in the neutron stars was constrained; we obtained an independent estimate of the expansion rate of the Universe which may help us in resolving the conflicting measurements obtained from other astronomical observations, and many more.

A massive effort is underway across the globe for building new detectors, upgrading the existing detectors and advancement of theoretical studies to promote rapid progress in the budding field of Gravitational Wave Astronomy, partly envisioning significant technological spin offs.

- **Second generation detectors:** The Advanced LIGO and Virgo detectors are being upgraded to the Advanced+ (A+) sensitivities. LIGO-India will also have the same configuration. The volume within which these can detect events of a given kind will be nearly ten times larger than the present detectors. The plans, site-selection and technology demonstration programmes for building next generation GW detectors are moving at a fast pace across the globe. There is an ongoing effort to design major upgrades of the present detectors, often referred to as LIGO-Voyager, which will use the existing sites, thus enormously cost-effective compared to the third generation detectors and highly relevant for LIGO-India.

- **Third generation detectors:** The international GW community is pushing two massive detectors to be built in the next two decades - the Einstein Telescope (ET) in Europe and Cosmic Explorer (CE) in the USA. According to the current plans, ET will be an equilateral triangle shaped underground detector with 10-km arms and CE will be an L-shaped 40-km long detector on the ground. Clearly, these are gigantic detectors, demanding enormous resources. The respective scientific community and the funding agencies are seriously pursuing these efforts: a site selection campaign across Europe was conducted for ET and a three year funding for conducting a concept study for CE has been granted.

- **Milli-Hertz detectors:** Frequencies of black hole mergers reduce with as their masses increase. It is well known that the Universe is full of supermassive black holes, though their exact numbers, distribution of mass, distance and other properties are barely known. Ground based detectors may never be able to operate below 1Hz due to seismic noise. Space based detectors with million-kilometer arm lengths will be able to detect the mergers of supermassive black holes. Also, they will be able to observe the inspiral phase of the smaller compact stars and alert when such a merger will be detected by ground based GW & EM observatories. These missions are developing high power Lasers for space and “drag-free” environment in spacecrafts using micro-thrusters, which may have broader application. There are two major international missions aiming for launches in the 2030s, Laser Interferometer Space Antenna (LISA) by the European Space Agency and TianQin by China.

- **Deci-Hertz detectors:** The milli-Hertz and the ground-based detectors leave a gap in the deci-Hertz frequency window. A detector in this band, apart from providing early alerts for stellar mass binary mergers and providing precise sky localisation in conjunction with the ground-based detectors, can observe interesting sources like intermediate mass black hole (IMBH) mergers and, perhaps, the enigmatic primordial gravitational waves generated in the very early Universe, right after the Big Bang, when the Universe was less than a second old and went through a phase of rapid expansion (the Cosmic Inflation). While Cosmic Inflation is a fundamental pillar of the standard model of Cosmology, presently, there is no direct evidence for it. Detection of primordial gravitational waves can provide a smoking gun evidence for Cosmic Inflation and pin-point its correct theoretical model. At present there is no funded mission in the Deci-Hertz band. With the expertise of the Indian space agency, and with the growing LIGO-India experimental community, India may be able to lead a future Deci-Hertz Gravitational Wave space mission, perhaps with international collaboration.

- **Other detectors**: Pulsar Timing Array (PTA): Pulsars, which are spinning neutron stars, emit pulses at very precise intervals. GW passing through the line of sight between pulsars and the earth perturb the delay in receiving these pulses from different pulsars in a coherent way, enabling us to detect the source of GW. A well understood and calibrated set of pulsars, called the Pulsar Timing Array (PTA), monitored with highly sensitive modern radio telescopes, can be used for this purpose. The uGMRT is a part of the pulsar timing array programme. Very low-frequency (nano-Hertz) signal from pulsars, that may be attributed to GW, has been recently detected by the participants of the International Pulsar Timing Array, that also includes the Indian Pulsar Timing Array (InPTA) group. This result is a major step for GW at nano-Hz frequencies. The Square Kilometer Array (SKA) has excellent prospects of detecting GW from inspiralling supermassive black holes.

3.7 Solar Telescopes

The Sun is a unique astrophysical system, not only providing a window to understand plasma astrophysical processes in the Universe through spatially resolved observations, but also affecting humanity directly and impacting our space-reliant technologies. This realisation over the last several decades – with our ever increasing reliance on space assets – has led to concerted global efforts both by advanced space-faring nations as well as international agencies to explore the Sun. These endeavours include the already functional, state-of-the art Daniel K. Inouye Solar Telescope (DKIST) – a 4-m class telescope in Hawaii funded by the United States (US) National Science Foundation and the under-development, European Solar Telescope, a 4.2-m class telescope being developed by a consortium of countries and funded by the European Union.

Multiple ongoing space missions of the US National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA) are currently observing solar dynamic activity, solar space storms and its impact on the Earth's magnetosphere. The two major workhorses in this regard are ESA's SOlar and Heliospheric Observatory (SOHO) and NASA's Solar Dynamics Observatory (SDO) which have been observing various aspects of solar activity, including its internal flows, surface magnetic fields, atmospheric dynamics and radiation. Other ongoing missions such as Advanced Composition Explorer (ACE) and WIND are making in-situ near-Earth particle and magnetic flux observations that perturb geospace and have space weather consequences. Notably, two pioneering missions have recently joined this fleet of space-based solar observatories. The major goals of ESA's Solar Orbiter mission with a novel out-of-ecliptic orbit are to observe the Sun's polar magnetic fields that determine the strength of future solar activity, constrain solar high latitude plasma flows and observe coronal mass ejections and dynamic activity from novel vantage points. The major goals of NASA's Parker Solar Probe (PSP) mission are to make in-situ observations in the extended solar outer atmosphere near where the solar wind originates and constrain the dynamics of solar magnetic transients in the innermost sanctum of the heliosphere. These satellites are generating unique new constraints on how solar activity is born, how they evolve through the Sun-Earth system and impact our space environment.

The recently launched India's first solar space mission, Aditya-L1 will observe solar atmospheric dynamics and constrain properties of the solar corona including coronal magnetic field measurements. The spacecraft will also make in-situ measurements of solar wind and interplanetary magnetic storm properties to understand their physical evolution and terrestrial impact. However, India does not yet have any large solar telescopes on ground that can complement the space facility.

To translate solar observations and computational models to actionable space weather understanding and predictions to benefit their nations, many countries have dedicated further resources. The US National Oceanic and Atmospheric Administration (NOAA) has created the multi-agency Space Weather Prediction Center, the United Kingdom's Met Office has a Space Weather Unit, and the ESA Space Weather Office provides space weather services and information for Europe. India does not yet have any dedicated multi-agency centre for space weather predictions.

The United Nations Office for Outer Space Affairs (UNOOSA) formally recognizes the importance of space weather as a phenomenon that impacts all member states and encourages international initiatives targeting the understanding and assessment of space weather as a peaceful means of exploring space that benefits humanity.

3.8 Computational Astrophysics

Computational astrophysics is now using the peta-scale facilities and gearing up to exploit the upcoming exa-scale facilities to improve theoretical modelling of many of the questions discussed above. Computational astrophysics involves development and implementation of efficient algorithms that scale well on supercomputing platforms. Considerable work has been done in developing computational models of the Sun and solar activity, N-Body simulations, relativistic simulations for dark energy, hydrodynamic simulations of formation and evolution of galaxies and intergalactic medium, magneto-hydrodynamic simulations of the evolution of magnetic field in the inter-stellar medium and stars, etc. Magnetohydrodynamic 3-D simulations of protoplanetary disc have been developed to study the complex physics of protoplanetary disc and planet formation. These simulations have uncovered various instabilities which might potentially help us explain the incredible fast rate of planet formation, as well as stellar mass growth via accretion disc. Numerical relativity simulations have been applied for study of gravity waves and other applications. 1-D and 3-D hydrodynamic models have been developed for simulation of supernova explosions and mergers of compact objects. All these works have resulted in some very significant findings. Considerable work has also been done on the development of specialized hardware for scientific calculations. This progress has enabled improvement in the modelling of a number of astrophysical problems, and also in the development of specialised hardware for telescopes and instruments. For example, in India, the developments in rapid data analysis enabled upgradation of the GMRT backend in 2010, and has also been a critical component of the development and implementation of the upgraded GMRT in 2020.

4 STATUS OF NATIONAL R&D EFFORTS

Research in astronomy and astrophysics in India encompasses a wide range of topics in both theoretical and observational areas. Indian astronomers have made several notable contributions to the world of astronomy right through ancient to modern eras, and have been innovative in utilising its relatively limited resources in both ground and space-based astronomy, as well as utilising facilities available elsewhere. Astrophysics groups at ARIES, IIA, IISc, IMSc, IUCAA, PRL, RRI, TIFR and in many Universities like Delhi University, Jamia Milia Islamia, JNU, Osmania University, Pt. Ravishankar Shukla University, Panjab University, Presidency University Kolkata (to name a few), and several central universities, several IITs and IISERs, NISER, IIST and NITs are actively involved in research in astronomy and astrophysics.

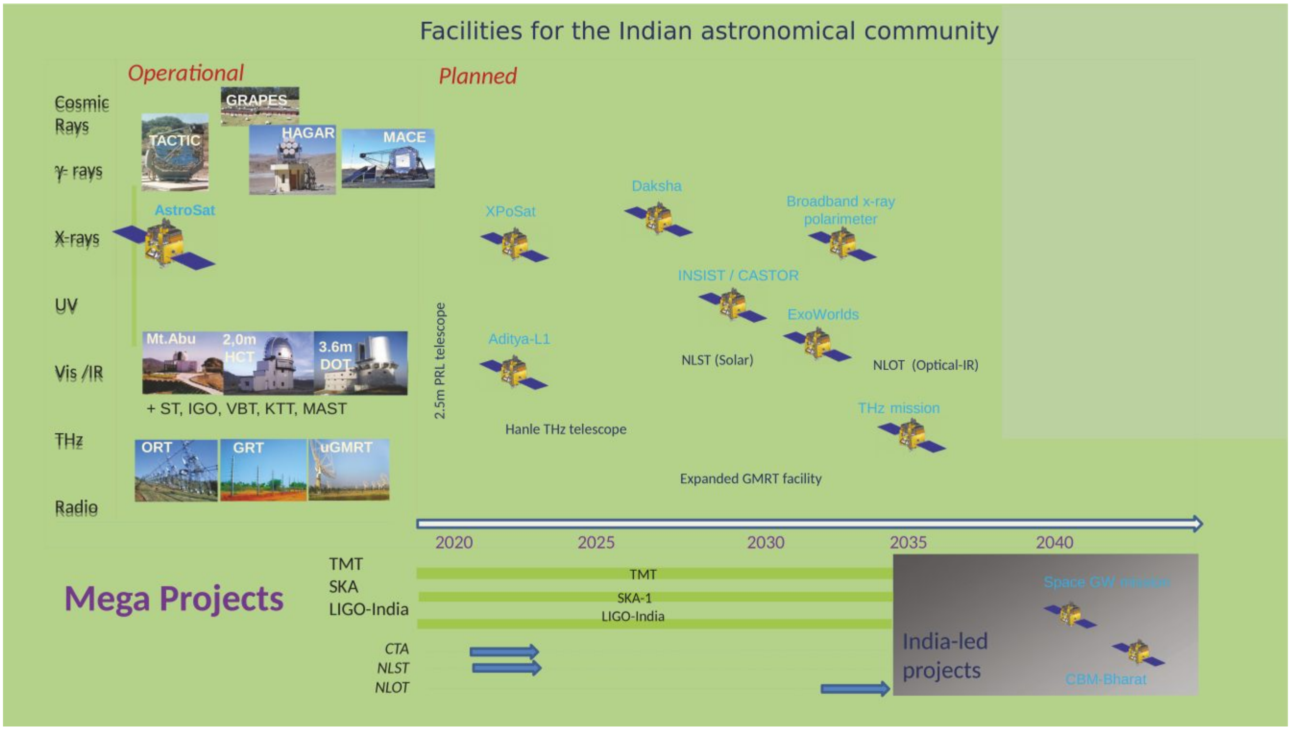

Figure 3: *A broad layout of Indian ground & space-based multi-wavelength astronomical facilities. The figure highlights existing/ongoing observational facilities along with those proposed, including astronomy related mega-projects. The visualization clearly indicates well-defined science and technological goals to conduct frontline science, using cutting-edge technology with industry engagements, leading towards large societal benefits in the national interest.*

Modern astronomy in the country can be traced to the setting up of the Madras Observatory in 1786, which later moved to Kodaikanal with the establishment of the Kodaikanal Observatory in 1899. These observatories led to the production of "The General Catalogue of 11000 Southern Stars" in 1843 and the discovery of the "Evershed Effect" from Kodaikanal in 1909. Observatories in India were part of Carte du Ciel, the first international project to produce a photographic atlas of the sky starting in 1890s. Post-independence, the efforts of renowned observational astronomers such as Vainu Bappu, Govind Swarup, V. Radhakrishnan, Arvind Bhatnagar (to name a few) saw the establishment of (then) state-of-the-art observing facilities in the country. The establishment of the optical observatories in Kavalur (in the South) and Nainital (in the North) in the late 1960s / early 1970s led to the discovery of the atmosphere around Jupiter's moon Ganymede, the discovery of the outer rings of Uranus, discovery of asteroids, observations of novae and star clusters. Observations of the Sun in the radio region began as early as the 1950s. However, it was with the setting up of the Ooty Radio Telescope operating in the 326.5 MHz radio region and the Gauribidanur Radio Telescope operating in the decameter region, both in the 1970s, that radio astronomy developed in a significant manner.

The country, in the 1980s, saw the development of the 2.3-m Vainu Bappu Telescope. This indigenous optical telescope was the largest optical telescope in Asia, when commissioned in 1986. The Giant Meterwave Radio Telescope (GMRT), yet another indigenous, world class facility, was built in the following decade. It has been available for observations to the national and international community since 2002. India's first astronomy space mission AstroSat, launched in 2015 is yet another indigenous development widely recognised and appreciated by the international community. The scientific achievements of the country in the field of astronomy and astrophysics has now evolved towards participating in a few frontline international mega-projects proposed to be operational in next few years, and also development of state-of-the-art national facilities (see Figure 3).

Indian scientists have also made significant contributions to the analysis of data from large survey projects like SDSS, Planck, WMAP, etc. Indian astronomers have also made important contributions using international observing facilities through competitive proposals. India has also progressed in step with the world in providing local repositories of archival observations through platforms like the Virtual Observatory India, the Kodaikanal Solar Observatory Digitized Data Archival System (a repository of data obtained from Kodaikanal for over 100 years), GMRT Online Archive (GOA), the ISRO Science Data Archive for AstroSat Mission, etc.

Theoretical astrophysics is an area where India has made significant contributions, ranging from solar physics, stellar astrophysics, galactic dynamics, to extragalactic astronomy, gravitation and cosmology and gravitational waves. There have also been many contributions in computational modelling of astrophysical processes in all these areas as well as in processing of large data sets. Indian scientists have produced many seminal works, especially in gravitation and cosmology. The works by stalwarts such as Bishveshwar Dutt, V.V. Narlikar, Amal Kumar Raychaudhuri, P.C. Vaidya, C.V. Vishveshwara and Jayant Narlikar stand testimony to this. Indeed, Einstein's paper on General relativity was first translated into English in India. Early work on relativity included that of the collapse of pressureless stars to singularity, on expanding universes and the derivation of the Raychaudhuri equation that showed that anomalies are inevitable in general relativity, which is the basis of singularity theorems given later by Hawking and Penrose. Another important work was that of the derivation of a realistic metric representation for stars, accounting for the radiation emitted by stars. One of the most important results underlying the emission of gravitational waves by a blackhole merger is that of quasi-normal modes. This result showed that this radiation depends only on the mass of the black hole for a non-spinning black hole. Later, this was generalised to rotating black holes where it also depends on the spin on the black hole. Astronomers hope to use this to establish the final mass of a black hole with improved observations of gravitational wave signals. Relativistic, direct action-at-a-distance theories in the cosmological context and the conformal theory of gravity are two other areas with significant contributions.

We provide below science highlights by Indian astronomers, enumerating key areas where Indian scientists have made significant contributions in the last few decades. Also provided in this section is a brief on the ensemble of astronomy facilities available in the country.

4.1 Science Highlights

4.1.1 The Sun

Solar physics has been one of the longest pursued research disciplines in the country. Several groups in the country are engaged in the observations of and modelling the Sun and its activity. The aspects of study range from solar structure, solar atmosphere, helioseismology, study of the magnetic field to its effect on solar activity and its impact on space weather, etc. Considerable work was also done on the solar neutrino problem that was finally resolved about two decades ago.

Magneto-convective processes in the photosphere and sub-photospheric layers of the Sun cause structuring of the magnetic field over a broad range of scales leading to flux concentrations. These dynamically important flux concentrations that occur at all layers of the solar atmosphere are responsible for almost all activity on the Sun, including heating of the upper atmospheric layers and the various eruptive phenomenon that drive the space weather. Researchers in the country utilise the various multi-wavelength data available through ground and space based observatories, both within the country and international in the studies of such phenomenon, that also includes detailed theoretical modelling.

Long-term solar observations (at low resolution) have been carried out systematically at the Kodaikanal Solar Observatory (KSO, IIA), the Udaipur Solar Observatory (USO, PRL) and ARIES. Daily photographic images of the Sun in white light continuum, CaII K emission and in Hα (in the form of spectroheliograms) have been obtained from the KSO since 1905. Since the late 1980s the photographic plate records have been upgraded to digital CCD records. The 100-year old photographic data have all been digitised and are made available for use through the KSO Digitized Data Archival System. These data are being used by both national and international solar astronomers for long term studies of solar activity.

Ground based radio telescopes at Ooty (TIFR) and Gauribidanur (IIA) have focused on characterizing the solar corona, solar wind and interplanetary perturbations during propagation of solar storms. Ground based magnetometer networks operated by the Indian Institute of Geomagnetism, GNSS (Global Navigation Satellite Systems) networks and ionospheric field stations located at various parts of India have been involved in characterizing the state of the ionosphere and geomagnetic storms in response to solar forcing. In the context of translational space weather prediction research, development of indigenous computational models for forecasting the solar system space environment and data analytics-based space weather forecasts (utilizing Artificial Intelligence and Machine Learning based approaches) are still in nascent stages. The multi-institutional Center for Excellence in Space Sciences India (CESSI) located at IISER-Kolkata has focused recently on translational space weather research and has been successful in developing indigenous computational approaches for space weather forecasting.

4.1.2 Solar System Objects

Photometric, spectroscopic and polarimetric observations of comets have been the main areas of research in the studies of solar system objects. These include the study of the impact plume of NASA's Deep Impact probe on the comet Tempel-1, based on which the effects of sublimation and diffusion in comets were inferred. Based on imaging and spectroscopic observations in the optical and infrared, the interstellar comet 2I/Borisov was shown to have a chemically heterogeneous surface, having variation in abundance of carbon chain molecules and dust to gas ratio similar to solar system comets. Studies of comets also include modelling of various cometary structures, especially cometary jets, dust grains, shells and fans. Understanding of the mass, angular momentum, magnetic field structure of different planets, comets, and other minor bodies of the solar system are some of the other topics that have been pursued. Genesis of magnetic field structure of solar system objects from the catastrophic events (such as bombardments with comets and asteroids) have been explored. It is shown that the genesis and diverse intensity of magnetic field structure of terrestrial planets (such as Mercury) and their satellites, and some of Jupiter's satellites, are mainly due to catastrophic events which occurred during the early history of solar system formation.

Indian astronomers are participating in international collaborations for the studies of NEOs. These include follow-up for orbit determination and photometric characterization of the NEOs. Observations of asteroids using the 0.7m wide field telescope located in Hanle, in collaboration with the ZTF survey group as a part of the international GROWTH collaboration, have led to the discovery of 6 asteroids, including asteroid 2020QG that had the closest approach to the Earth in recent times. *The longitudinal advantage of India's geographical location will be best utilised in the studies of NEOs with the availability of a network of wide field telescopes in the country that can be part of a larger international network of telescopes.*

4.1.3 Interstellar Medium

The interstellar medium is a main gas reservoir from which new stars are formed. Physical conditions prevailing in the ISM (metallicity, gas temperature and pressure, turbulence etc.) are linked to the stars and their evolution. Indian astronomers have contributed to our understanding of star formation, nature of H I and H II regions, photo-dissociation regions, dust formation, molecular chemistry, cosmic ray propagation and excitations, SNe-ISM interactions and measuring the power-spectrum of ISM turbulence etc. In the radio wavelengths, Indian astronomers have made unique contributions to the studies of radio recombination lines, H I emission and absorption from galactic ISM, establishing the link between 21-cm spin-temperature and H_2 rotational excitation temperature, measuring the rotation and dispersion measures using pulsars, measuring the power-spectrum of density fluctuation using H I spectroscopy towards SNe remnants. These studies involve spectroscopic observations using ORT, GMRT and other international radio facilities like VLA, WSRT and ATCA. In the optical front, original contributions were made on measuring gas phase metallicity and dust, nature of molecular excitations, mapping molecular and dusty star forming regions. These studies mostly used high resolution spectroscopic observations (from Indian and other international facilities including space telescopes) and polarisation measurements using imaging and spectropolarimetry available in Indian facilities. In the theoretical side, important contributions were made in understanding the multi-phase nature of the ISM, formation and excitations of complex molecules and dust and physical modelling (equilibrium and non-equilibrium) of photo-dissociation regions.

Indian astronomers have also contributed to the measurement and theoretical estimation of ionizing UV background. Utilising the archival data from the Galaxy Evolution Explorer (GALEX) mission, the diffuse ultraviolet cosmic background in two wavelength bands (FUV: 1530 Å and NUV: 2310 Å) was mapped over almost 75% of the sky. Most of the diffuse flux was found to be due to dust-scattered starlight having a strong correlation with the 100 μm Infrared Astronomy Satellite (IRAS) flux.

4.1.4 Formation of Stars and Planets

Formation of stars and planets is an extremely important area of astrophysics. For instance, although the phenomenon of star formation is being studied for decades, the mechanism for formation of high mass stars relative to the low-mass star formation processes is still poorly understood. Indian astronomers have made significant contributions in this area through the studies of specific star forming regions, dark molecular clouds, young stellar objects, star clusters, etc., using data obtained from Indian facilities as well as other space and ground based facilities. Some highlights are the studies of star formation processes in the inner Galactic regions. These are particularly important to understand as star formation happens in an environment of relatively higher density and metallicity. Based on studies of the star forming regions, astronomers have also contributed to the estimates of the initial mass function and star formation rates in specific regions of our Galaxy as well as in other nearby galaxies.

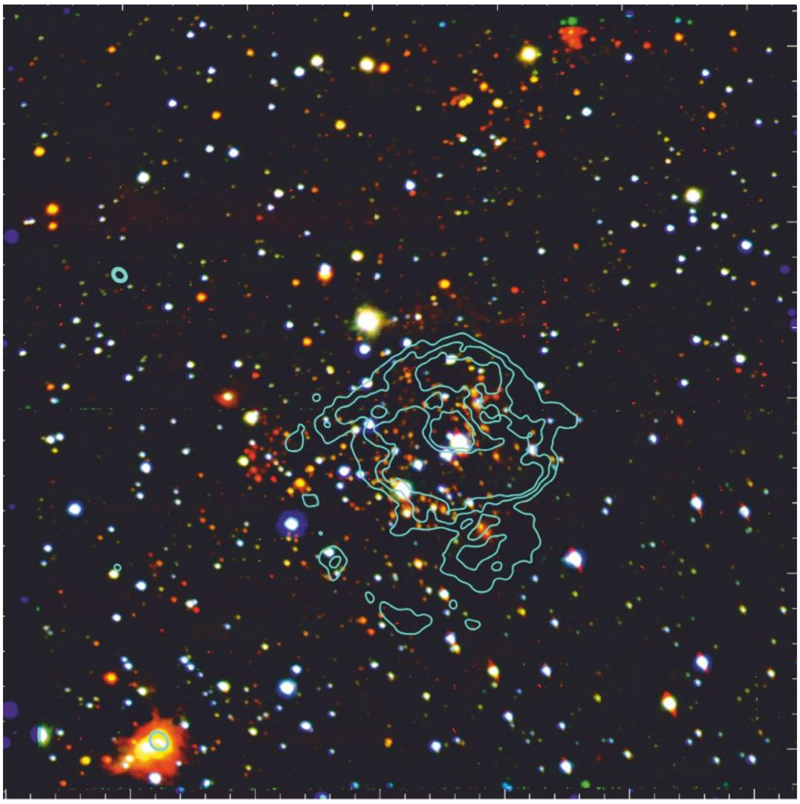

Figure 4: *Colour composite image generated using data from ARIES 1.3m DFOT (V -band, blue colour), 2m HCT - TRISPEC (J-band: green, K band: red) overlaid with GMRT radio contour (1280 MHz) of the star forming region Sh2- 305, which is an HII region undergoing star formation due to impact of strong UV radiation from a nearby massive star. In the center is a young star cluster that is found to be embedded in a molecular cloud. The red sources are mostly embedded young stellar objects as seen from the deep K-band image that have formed mostly due to the impact of a strong UV radiation from a massive star (as seen by radio continuum contours). Figure credit: adapted from Pandey et al. 2020, Apj, 891, 81; Dewangan et al. 2020, ApJ, 898, 172*

Considerable work has been done on the theoretical front in the study of formation of planets and minor bodies like asteroids. There have been several detailed suggestions made regarding contributions to energy inventory that helps in understanding differentiation in planets. Similarly, there has been some recent work on the formation processes for asteroids that seem to be like rubble piles. Simulation based work on instabilities in the ISM that eventually lead to formation of stars has been done by several groups. These detailed calculations use MHD simulations in a multi-phase ISM.

4.1.5 Stellar Clusters

Globular clusters (GCs) are densely packed collections of ancient stars. Roughly spherical in shape, these contain hundreds of thousands, and sometimes millions, of stars. Studying them helps astronomers estimate the age of the Universe or figure out where the center of a galaxy lies. RR Lyrae stars are low-mass, typically metal poor, Population II stars that are located within the so-called classical instability strip. Their apparent large-amplitude brightness changes are due to oscillation in the radial modes: radial fundamental mode (RRab stars) or radial first overtone mode (RRc stars) or simultaneous pulsation in these two radial modes (RRd stars) makes them as excellent distance indicators. Identification of new RR Lyrae stars belonging to GCs, study of the nature of oscillations and determination of physical parameters have been some of the key topics of research in the study of GCs. Another class of intriguing stars are the blue straggler stars (BSS). These are stars that are more luminous and hotter (bluer) than the stars at the main sequence turnoff in clusters, i.e. they appear to be younger than the other stars in the cluster. One explanation is that these are stars that have been formed through merger of stars within the cluster. However, in the case of less dense star clusters and in outer regions of the clusters, there still could be some BSSs formed via mass transfer. Using the far-UV capabilities of the AstroSat, Indian astronomers detected far UV bright BSSs in star clusters, measured their basic parameters and showed some of them to be mass transfer systems.

Open clusters (OCs) are collections of stars that share similar ages, chemical compositions, and are at similar distances from us. These qualities make open clusters important cosmic laboratories for studies of fundamental astrophysics such as: the formation of stars, stellar evolution, dynamical interactions between stars, and the chemical and dynamical evolution and structure of the disc of the Milky Way. The study of open clusters of the stars is a traditional field with astronomers in the country. The findings of their studies include determining the cluster membership, stellar population and age of the cluster, study of variable stars in the cluster, and the structure of the Galactic disc.

4.1.6 Stellar Abundances and Chemodynamics of the Galaxy

The study of stellar abundances and Galactic kinematic and chemical evolution have been the main forte research of several astronomers in the country. Detailed abundance analysis of metal-poor stars through targeted surveys have led to new understanding of these objects. For instance, the observed abundance patterns of some of the carbon enhanced metal poor (CEMP) stars showed that abundance pattern in these objects are well reproduced with the i-process model predictions. Analysis based on different elemental abundance ratios confirmed low-mass former AGB companions for these objects. A detailed study of abundances in the globular cluster Omega Centauri led to the discovery of helium rich stars in the cluster. This discovery is of importance as it indicates multiple populations in the globular cluster contrary to the general belief of these objects having a single population. Indian astronomers have also made important contributions to measuring the abundance pattern in metal poor gas in the early Universe that are compared with Galactic metal poor stars to understand the early chemical history.

In a recent study led by Indian astronomers, robust observational evidence was provided which indicated that Li production in stars is common. Using data from large spectroscopic surveys such as GALAH and LAMOST, combined with astrometric data from Gaia, and astroseismology data from Kepler space telescope, they made a systematic investigation of Li enhancement in evolved stars and found the enhancement to be common among the low-mass giants associated with He-core burning phase, also referred to as Red Clump stars. Observational evidence for Li enhancement during the helium-flashing phase was established. This result is the first observational evidence of the theory developed in 1960s for converting an inert, electron-degenerate He-core into a fully convective He-burning core by a series of core He-flashes, a phase that lasts for about 2 million years.

Combining ground based high resolution spectroscopy and astrometry of stars in the Solar neighbourhood (within 200 pc) from the Hipparcos space mission the Galactic disc was decomposed into thin and thick discs. It was found that the stars in the thick disc are old (~ 8 - 10 Gyrs), metal-poor ([Fe/H] ~ -0.6) and found to have distinct kinematic motions and chemical composition different from that of thin disc population. The thick disc population is believed to be the result of a major merger of a metal-poor dwarf galaxy when the Milky Way was just 1-2 Gyrs old.

An extensive study was carried out based on 300,000 stars using the SDSS-DR7 database and it was shown that carbon production happened in the early Galaxy, through massive stars, either during the wind or through faint SNe. Supporting evidence was found in the study of carbon abundance in Bootes dwarf galaxy. Similar galaxies are thought to be the first galaxies formed in the Universe and building blocks of our Galaxy halo. These results have implications on the early chemical evolution, feedback and critical metallicity for the first low mass star formation and so on.

4.1.7 Stellar and Exoplanet Atmospheres

Application of radiative transfer to understand line formation and polarisation has been a core area in theoretical studies of the stellar and solar atmospheres. Polarised spectral line formation in solar and stellar atmospheres is one of the front-line areas that is being pursued. Polarisation of spectral lines provides us with an important diagnostic tool to decipher the thermal, magnetic, and dynamic nature of the solar and stellar atmospheres. For this purpose, quantum and classical theories of light scattering on atomic systems were formulated and efficient numerical methods were developed to solve the concerned polarised radiative transfer equation.

It is now increasingly clear that the atmospheres of the young, self-luminous extrasolar giant planets imaged to date are dusty. Planets with dusty atmospheres may exhibit detectable amounts of linear polarisation in the near-infrared. The asymmetry required in the thermal radiation field to produce polarisation may arise either from the rotation-induced oblateness or from surface inhomogeneities, such as partial cloudiness. Using a self-consistent, spatially homogeneous atmospheric model and a multiple scattering polarisation formalism for this class of exoplanets, it is shown that polarisation of the order of 1 per cent may arise due to the rotation-induced oblateness of the planets. Polarised radiation from self-luminous gas giant exoplanets, if detected, provides an additional tool to characterize these young planets and a new method to constrain their surface gravity and masses.

A state-of-the-art numerical code that generates new grids of transmission spectra for hot Jupiters was recently developed by astronomers at IIA. The synthetic spectra obtained through the detailed modelling, were compared with the available observed spectra obtained by using HST and Spitzer Space telescope. The JWST, the upcoming ARIEL space telescope and the TMT will be able to obtain high resolution transmission spectra of exoplanets during transit spectra. *The numerical code developed by Indian astronomers will provide an accurate analysis and interpretation of the observed spectra and hence probe the exoplanetary atmosphere.*

Indian astronomers were part of an international campaign to study the transit signals due to planets around the ultra cool dwarf TRAPPIST-1 (2MASS J23062928-0502285). The extensive observations indicated the star to be hosting multiple planets. The transit of its planets is expected to give rise to significant asymmetry and produce phase-dependent polarisation. Adopting the known stellar and planetary physical parameters and employing a self-consistent cloudy atmosphere model of the M8 dwarf star, the transit polarisation profiles and the expected amount of polarisation of Trappist-1 during the transit phase of each individual planet, as well as that during the simultaneous transit of two planets, were presented and shown to be within the detection limit of a few existing facilities.

4.1.8 Galaxy Formation and Evolution

Formation and evolution of galaxies is intimately connected with star formation and feedback processes that regulate star formation in galaxies, formation and growth of super-massive black holes, and the physical state of the intergalactic medium as it exchanges matter and radiation with galaxies through a variety of processes. Formation of the first generation of stars and galaxies also leads to ionisation of the intergalactic medium and this is an epoch of special interest to astronomers. India has a large community of astronomers working on the epoch of reionisation and the intergalactic medium. Using available observations of distant quasars, galaxies and cosmic microwave background radiation, they have placed stringent constraints on the epoch of reionisation and the nature of ionising sources. This field will have a major boost in the SKA era with the observations of H I 21-cm signal from the epoch of reionisation. India also has a large pool of astronomers working on various aspects of IGM studies who are playing a very important role in mapping the redshift evolution of atomic and molecular content of the universe through radio and optical spectroscopy. Important contributions include: (i) IGM and CGM observations using both optical and 21-cm H I spectroscopy; (ii) detection of H I, C II, CO and mm emission from distant galaxies; (iii) understanding the properties and evolution of radio galaxies and quasars; (iv) studies of low frequency radio emission and X-rays from high redshift galaxy clusters and groups; (v) most accurate measurements of clustering properties and thermal evolution of the IGM and; (vi) mapping of meta-galactic radiation field that imprints the galaxy evolution and intervening material through radiative transport efforts in the Universe.

Key ideas on galaxy evolution have been proposed, in particular, during the late stages of evolution of galaxies wherein star formation slows down and sometimes comes to an abrupt end. Important theoretical contributions have been made in the modelling of CGM gas, galactic winds that populates CGM and IGM, analytical and numerical modelling of IGM including various feed back processes. The role of feedback from star formation and AGN activity on gas content in galaxy halos has been studied using simulations. Some models of dark matter allow for decay of dark matter particles into other particles. In such models it is possible for some of the energy to be released as photons. This leads to observable effects and Indian scientists have confronted such models with observations to put strong constraints on parameters of these models.

The dynamics of stars and gas in galaxies, as well as use of information about orbits of gas, stars and satellite galaxies to uncover the shape and structure of the dark matter halos of galaxies is an area where several key results have been published by Indian astronomers. Computational work on evolution of features like bars in galaxies and the impact of interaction between galaxies on star formation rate has also led to some very interesting results. Optical and radio observations have been used to measure the stellar and HI gas kinematics and rotation curves of normal and dwarf galaxies.

Indian astronomers, either lead or co-investigate several key large survey projects being carried out using SKA pathfinders like MeerKAT (in South Africa) and ASKAP (in Australia). Several Indian astronomers are co-investigators in dedicated experiments like The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) and the Hyper Suprime-Cam Subaru Strategic Program (HSC). Data collected through these surveys will provide deep insights into the formation and evolution of galaxies over the past 3 billion years.

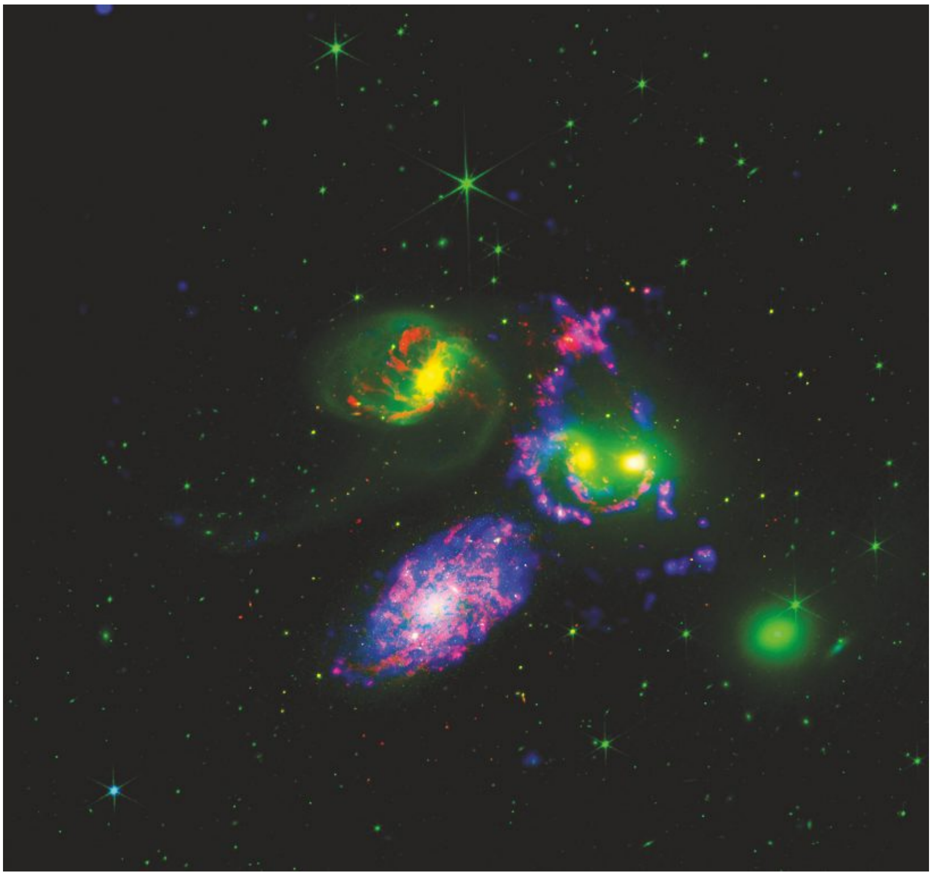

Figure 5: *AstroSat-FUV (UVIT) and JWST-IR (F770W) colour composite image of the Stephen's Quintet compact group of galaxies showing clumpy star-formation at the smallest scales. Figure credit: Joseph et al. 2022, RNAAS, 6, 180*

4.1.9 Large Scale Structure of the Universe

Theoretical modelling of formation of galaxies requires a clear understanding of the connection with formation of the large scale structure and dark matter halos where conditions are appropriate for formation of stars and galaxies. This understanding has been developed using a mix of analytical models such as the "halo model" and the theory of mass functions, semi-analytical models and approximations, and cosmological N-Body simulations. Indian astronomers have contributed to all aspects in this area with significant ideas that have been adopted by research groups all over the world. One idea that has been around for some time is that the presence of large scale magnetic fields in the Universe can influence the evolution of large scale structure and galaxy formation. This is an interesting possibility that needs to be explored as magnetic fields are the only other long range force other than gravity in a Universe that is charge neutral at large scales. This possibility has been explored in detail by Indian scientists and they have put strong upper limits on the possible strength of large scale magnetic field.

Observations of galaxies can also be used to test some of the basic assumptions of large scale homogeneity used in constructing cosmological models. Indian astronomers have used fractal measures to test this assumption and estimate the scale of homogeneity. Theoretical work relating fractal dimensions with the correlation function has also been used to connect two approaches that were considered disparate. Lastly, a new definition of the scale of homogeneity has been suggested that is based on inability to distinguish between the distribution of galaxies and a random distribution of points. Understanding the large scale distribution of galaxies through halo models is yet another area with significant contributions. This approach is also useful to study the distributions of ionised bubbles during reionisation etc.

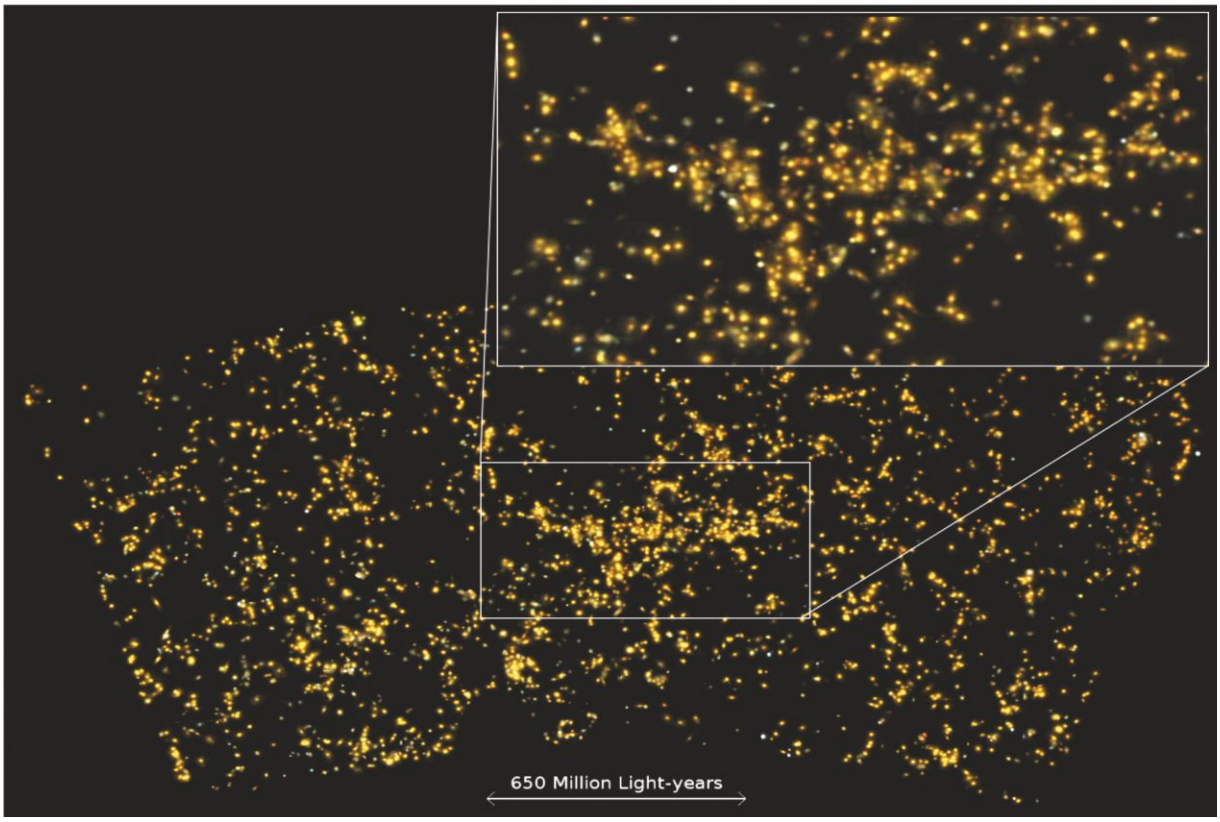

Figure 6: *Distribution of SDSS galaxies in the direction of the Pisces constellation. The central high density of galaxies is the Saraswati supercluster region (enlarged in the inset). Note that each point corresponds to a galaxy, and the typical size of a galaxy here is around 250,000 light years. Figure Source: IUCAA (adapted from Bagchi et al. 2017, ApJ 844, 25).*

Analysis of large scale structures using archival observations has been used to demonstrate the existence of a supercluster, named the Saraswati supercluster. This has been shown to be made up of a large number of clusters of galaxies and is one of the largest concentrations of galaxies of this size known till date. Apart from the usual statistical indicators of amplitude of clustering to characterize the large scale structure, topological constructs such as Minkowski functionals have been used to compare different models with observations. Similar techniques have been applied to study the distribution of radio sources in the sky and the cosmic microwave background radiation.

Indian astronomers have also made significant progress in developing and deploying methods that can be used for intensity mapping: a technique for tracking mass distribution using emission lines from atomic or molecular gas as a tracer.

4.1.10 Cosmic Microwave Background Radiation

The CMBR was predicted by George Gamow in the context of the Big Bang model of cosmology. This was observed by Penzias and Wilson who went on to get the Nobel prize for this discovery. Anisotropies in CMBR were predicted early on and detailed predictions were made in the context of inflationary models. These were detected observationally by COBE (COsmic Background Explorer) in 1992. Theoretical predictions and comparison with observations is based on a robust mathematical foundation. Indian scientists have contributed considerably to ideas and models, as well as detailed programs of comparison of theoretical models with observations to test fundamental aspects as well as detailed constraints on parameters of models. Fundamental aspects here refer to assumptions of isotropy, as well as statistical isotropy of perturbations. Whereas the program to constrain parameters focuses on the description of the Universe as well as the characteristics of perturbations that go on to give rise to the large scale structure and galaxies.

Indian astronomers have made significant progress in measuring the spectrum of radiation backgrounds, including the cosmic microwave background radiation. This requires development of broad-band receivers and detectors that have a uniform angular response over a wide range of frequencies. These are being used to measure that spectrum as this can yield considerable information about the epoch of recombination and the epoch of reionization, leading to an improved knowledge of various cosmological parameters and scenarios of galaxy formation. Indian astronomers played a key role in confirming one of the fundamental predictions of Big Bang, that of increasing temperature of CMBR with redshift. Using the limits on the deviation of CMBR spectrum from a perfect blackbody (the so called "spectral distortions"), interesting constraints on cosmological parameters and contributions to CMBR from sources like decaying dark matter etc., were placed.

4.1.11 Cosmology and the Early Universe

Observational evidence indicates that the Universe is undergoing an accelerated expansion at present. This is believed to be driven by dark energy, a component with unusual properties like an effective negative pressure. This component dominates the Universe at present. Considerable work has been done on modelling dark energy and its observable properties by groups in many different universities and institutes. Many groups have used a wide variety of observations and statistical tools to constrain properties of dark energy. A key question of whether observations can differentiate between different classes of models has also been addressed recently. Observations also suggest that the

Universe had undergone a rapid expansion phase in the very early stages. This phase is referred to as inflation and models for inflation were proposed in late 1970s and early 1980s. One of the key predictions of these models is the presence of perturbations at very large scales and this has been verified in observations of the cosmic microwave background radiation anisotropies. A number of research groups have contributed to constructing models for inflation, working out theoretical ideas related with inflation, confronting models of inflation with observations, etc. One critical idea related to inflation is the possibility that large scale magnetic fields were generated during this era. Much work has been done on ideas related to cosmic magnetism and its implications by groups in Indian institutes.

Abundance of clusters of galaxies has been shown to be sensitive to the power spectrum of fluctuations in matter density. Further, the evolution of abundance and the variation seen using different types of observations are sensitive to cosmological parameters like the total density parameter, baryon density parameter, etc. Observations of clusters in the optical, radio and X-rays have been combined to constrain cosmological parameters. Similar efforts have been made by astronomers to use the abundance of galaxies at high redshifts to put constraints on the mass of neutrinos. Constraining the baryon density of the Universe through the observations of Deuterium in metal poor gas in the early universe is yet another important study.

4.1.12 Gravitational Lensing

Gravitational lensing is a phenomenon by which light from a distant galaxy (object) is distorted by the gravitational effects of a foreground galaxy that acts like a lens, and makes the distant source appear distorted, but magnified, forming characteristic rings of light, known as Einstein rings. Gravitational lensing was observationally confirmed in 1919, also confirming Einstein's prediction using general theory of relativity. In the last five decades, observations of gravitational lensing of distant galaxies have been used to measure mass of galaxies and clusters, thereby confirming the presence of dark matter that outweighs normal matter by a factor of more than six. Observations from the Ooty radio telescope led to the discovery of a strongly lensed radio source PKS1830-211.

Gravitational lensing is an extremely good cosmological tool as it enables observations of distant objects. Indian astronomers have contributed significantly to the theory of gravitational lensing as well as modelling of mass distribution on observed lensing systems. In a study published in 1995, a new population of lensing sources were discovered in the Abell cluster based on sensitive VLA maps in 21cm. The past decade has seen a resurgence of interest in this field as upcoming surveys will increase the number of gravitationally lensed systems by more than an order of magnitude. Participating in several international collaborations, Indian astronomers have been studying gravitationally lensed sources to estimate the Hubble constant, measure the mass of galaxies, estimate the amount of dark matter in galaxies, etc.

A recent development in the field of gravitational lensing is micro-lensing of gravitational waves where the wave interference effects are important and geometric optics limit is not valid. Indian astronomers have contributed to development of ideas as well as detailed predictions for observations and have also participated in international collaborations in the search and detailed monitoring of micro-lensing events.

Distortions in the shape of background galaxies by the foreground large-scale structure (called “weak gravitational lensing”) provides an important probe of cosmological parameters and evolution of structures in the Universe. Weak lensing studies require high quality deep and sharp images. Indian astronomers are involved in such studies using various deep surveys carried out by international teams. Methods based on catastrophe theory have been deployed to predict the number of exotic image formations that can be expected in upcoming surveys, and it has been demonstrated that the expected number is much larger than earlier estimates if one uses realistic lens map models instead of idealized models.

4.1.13 Time Domain Astronomy

While time domain astronomy encompasses the study of variability in a variety of astronomical sources, the past few decades has seen an increasing dominance of the studies of transients. The availability of multi-wavelength observational facilities, combined with the longitudinal advantage of the India-based facilities has enabled notable contributions towards studies of transients such as novae, supernovae, gamma-ray burst sources and many other new classes of transients. The AstroSat, the upgraded GMRT and the 3.6-m DOT have added new dimensions towards studying various transients, adding value to expostulate the underlying physics. The combined set of observing facilities in the country have strengthened the international collaborative efforts in the field of time domain astronomy, paving path for the future.

The studies of nova systems, both during outburst and at quiescence is one area with significant contribution from India. Optical and infrared spectroscopic studies of the temporal evolution of nova outbursts have revealed

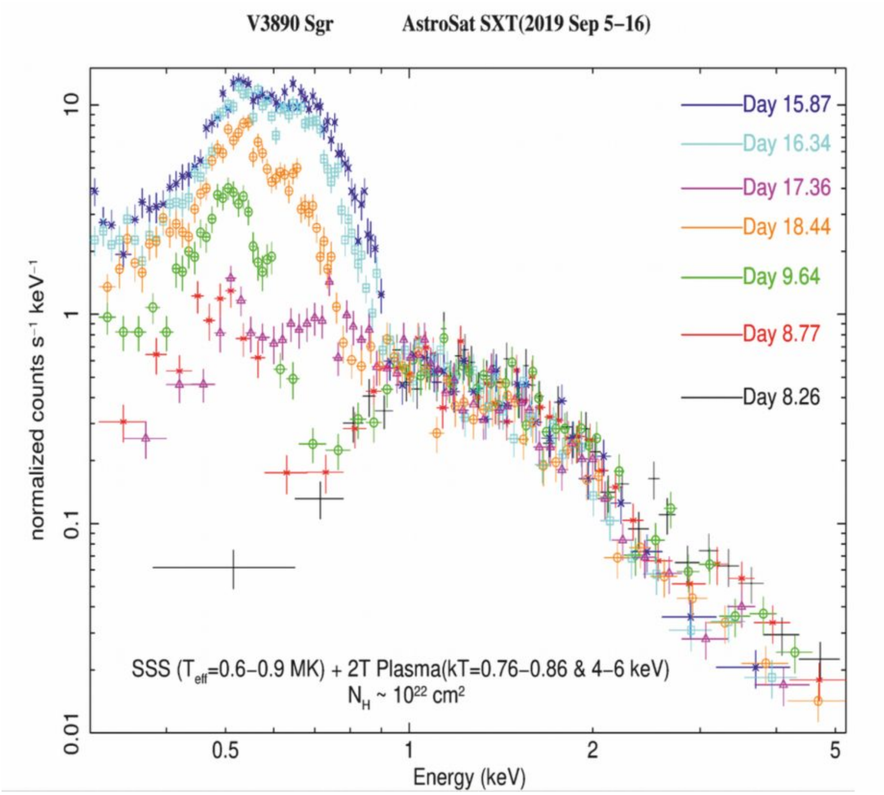

Figure 7: *Soft-Xray spectra of recurrent nova V3890 Sgr during the supersoft X-ray phase of the 2019 outburst. Based on AstroSat-SXT observations. Figure credit: Singh et al. 2021, MNRAS, 501, 36.*

complexities in the physical conditions of the various components of these systems. Based on long term spectroscopic monitoring during quiescence, the presence of a white dwarf primary was firmly established in recurrent novae with giant secondaries. Using observations during outburst, it was shown that the mass of the white dwarf in the recurrent nova U Sco is increasing. The first detection of low frequency synchrotron radio emission from a recurrent nova was made by the GMRT observations of the 2006 outburst of the recurrent nova RS Oph. AstroSat's SXT and UVIT are carrying out unprecedented high cadence observations of novae, catching the emergence of supersoft phase of a nova and its highly variable and poorly understood evolution on very rapid scales of minutes to hours. Observations of the recurrent nova V3890 Sgr using the AstroSat during its supersoft X-ray phase following the 2019 outburst provided the densest possible monitoring of a nova outburst from a low-Earth orbit. It demonstrated the fast evolution of the super-soft emission in this object, including a rapid first appearance on day 8.57 after the outburst, clearly establishing the presence of a massive white dwarf primary in the system. All these results are of immense importance in the studies of nova systems as potential single degenerate progenitors of supernovae of Type Ia.

Multi-wavelength observations of various types of SNe has been an active programme for the researchers in the country. The observations, made primarily using Indian facilities but also quite often combined with data from international facilities, typically range from pre-maximum to late post-maximum days. The major goals of these studies are to estimate the explosion parameters constraining underlying physical mechanisms, understand the host galaxy properties and interaction of the supernova with its immediate environment, in an attempt to understand the progenitors and explosion mechanisms of various types of supernovae.

The use of SNe Ia as cosmological probes requires an understanding of the homogeneity and heterogeneity of these system through detailed studies of the events occurring at low redshifts. This has been the main theme in the studies of SNe Ia that have led to a few important results. Early phase spectra of several events have shown the presence of carbon rich dust in their ejecta, indicating differences in the explosion channel. The studies of low luminosity Iax events have shown these supernovae to be the result of a pure deflagration explosion, most likely in a double degenerate system. Detailed analysis of the light curve of the nearby, normal Ia, SN 2014J, indicated the properties of the interstellar medium in its host galaxy to be different from that of the Milky Way.

Various types of core collapse SNe (CCSNe) have been studied extensively. Starting with a detailed spectroscopic monitoring of the nearby H-rich supernova SN 1987A (from VBO) that led to the identification of barium in the hydrogen-rich CCSNe, several CCSNe have been studied to understand dust formation, circumstellar material (CSM) interaction and for constraining the underlying physical mechanisms. While the very early phase observations in the optical have enabled the detection of shock breakout (e.g. in SN 2018hna) and indications of CSM interaction (e.g. SN 2016gfy, SN 2019uo), the late time radio observations of several CCSNe (e.g. SN 1993J, SN 2004dj, SN 2010jl) have enabled constraining the physical parameters of the CSM. A targeted survey of 24 recent CCSNe in the low frequency radio using the GMRT led to the detection of just about 6 events. Based on polarimetric observations, and observations during the late phases, presence of dust and asymmetry in the ejecta have been inferred for many supernovae. Such studies provide important constraints on the mass loss in the progenitor during its evolution. Long term monitoring of the stripped envelope Type Ib SN 2001em using the GMRT indicated interaction between the supernova ejecta and the dense shell indicative of a massive binary system as possible progenitor. Comparing theoretical simulations of light curves and synthetic spectra with observations, explosion parameters and progenitor properties of several supernovae have been studied. These studies indicate 12 - 20 $M_{\odot}$ progenitors in type IIP supernovae, Wolf-Rayet progenitors (20 - 25 $M_{\odot}$) in the case of Ib/c supernovae, while the study of the type Ib supernova iPTF13bvn provided the first evidence of a binary progenitor in type Ib supernovae.

The study of optical and radio afterglows of GRBs during the past two decades has benefited greatly by the longitudinal advantage of Indian sub-continent. Beginning with the first ever afterglow detection for a GRB in 1999, GRB 990123, well-calibrated photometric and spectroscopic data observed using Indian optical-NIR facilities and the GMRT clubbed along with data obtained with other collaborative facilities have been employed to constrain the nature and underlying physics of many of these energetic stellar explosions. These studies have helped us to contribute towards deciphering the jet geometry, nature of possible progenitors and their ambient media, etc. Multi-wavelength observations using Indian facilitates of bursts like GRB 201004, GRB 021211 have shown the presence of diversity in these events. Extensive studies of some of the rare GRBs associated with underlying broad-lined type Ic SNe (e.g GRB 0303029/SN 2003dh) using optical and radio telescopes and have helped to constrain not only the non-thermal synchrotron afterglow models but also helped in understanding the properties of the underlying SNe indicating towards collapse of a massive star as possible progenitor. On-board high energy instruments of AstroSat have also observed temporal, spectral and polarimetric properties of a few hundred of GRBs which have greatly helped to improve our understanding about prompt emission properties of GRBs including magnetic field structure within the jet and shock physics. Polarisation has been detected in many GRBs observed using AstroSat-CZTI. Spectropolarimetric studies of the prompt emission of GRBs using X-ray and γ-ray data may provide clues to understand their physical origin better.

Indian astronomers are contributing significantly in the study of fast transients through national and international collaborations. Based on long term multi-wavelength monitoring, FBOTs AT2018cow and AT2020xnd were studied in detail and it was shown that the multi-wavelength behaviour of these objects is consistent with the model of an accretion powered jet following the direct collapse of a massive star to a black hole. Indian astronomers are collaborating in the international Canadian Hydrogen Intensity Mapping Experiment (CHIME) project, through which over 500 FRBs were detected and it was shown that these sources have a uniform distribution in the sky. In a recent uGMRT observing campaign of FRB 180916.J0158+65, it was shown that this source has a 16.35-d periodicity of its active cycle. Analysis pipeline for detecting transients in the radio wavelengths are being developed for the upgraded Ooty radio telescope. Observations of some of these transients exhibiting lensed character can be used to put constraints on cosmological parameters and to improve lens models. While theoretical studies were done in this area in the past, recent studies include observational aspects as well with increasing number of transients.

4.1.14 Compact Objects

Compact objects include white dwarfs, neutron stars, and stellar-mass and super-massive black holes. These exotic objects are nature's laboratories to study physics at extreme conditions, e.g., densities, temperature, magnetic field, gravitational acceleration significantly higher than what could be produced in our laboratories. Groups in many different institutions have worked on these objects from a very diverse set of perspectives. Indian scientists have made very significant contributions to the understanding of the structure and evolution of compact stellar remnants like neutron stars and black holes. Modelling of compact objects with accretion of gas and related phenomena using theoretical and computational approaches is being pursued by several groups.

Newly discovered Galactic X-ray sources such as Cyg X-1, Cyg X-3, and Sco X-1 were observed using Indian balloon-borne instruments in the 1970s and 1980s, in which the variation of intensity and energy spectrum were noted. Such observations contributed to the eventual identification of these sources as a binary system containing a neutron star or a black hole. In the 1990s, similar observations with newer telescopes continued. For example, the hard X-ray pulsar GX 1+4 was observed using the balloon-borne Xenon filled Multi-cell Proportional Counter (XMPC) telescope, which provided precise measurement of its pulse period. Using observations from the Indian X-ray Astronomy Experiment (IXAE) onboard the Indian satellite IRS-P3 rapid changes from a high-soft to a low-hard state of the black hole X-ray binary GRS 1915+105 were studied. Presence of an event horizon in this object was also proposed using the observed X-ray burst behaviour. Such observations contributed in characterizing the ongoing dynamical processes and emission mechanisms in the inflow of matter near compact objects. Very detailed theoretical models of the accretion flow around black holes and neutron stars were developed by theorists that were able to explain various observational details such as quasi-periodic oscillations in their emission, and the possible presence of outflow.

Pulsars are rapidly spinning neutron stars in which the direction of the magnetic field is misaligned with the rotation axis. Indian astrophysicists established the limit on the accretion driven spin-up of a neutron star known as the 'spin-up line' and predicted the existence of a population of 'spun-up' pulsars that was later validated by the discovery of millisecond pulsars. Based on magnetospheric emission mechanisms it was predicted that millisecond pulsars may be strong emitters of γ-rays, which was later confirmed by the observations of Fermi γ-ray Space Telescope. Significant inroads have been made into the formation process of neutron stars in interacting binaries, the subsequent evolution of such systems, and stellar interactions leading to the formation of binary pulsars, millisecond pulsars and pulsars in globular clusters. Substantial progress has been made in our understanding of the decay of the magnetic fields of single radio pulsar as well as whether the magnetic field evolution in binary systems is driven by accretion.

Observations of pulsars in the radio with a view to understand the emission geometry and the underlying physical mechanism has been one of the key science areas carried out with the GMRT. These observations have led to the detection of multiple components in the pulse profile of many pulsars. Relativistic models have been generated to study the pulsar emission and polarisation considering detailed geometry of the emission region, rotation, and modulation. Simulating a set of typical pulse profiles, the role of viewing geometry, rotation, and modulation in the pulsar polarisation profiles has been analysed.

In the last decade, Indian astrophysicists have contributed to explaining the physical origin of the cyclotron resonance scattering feature (referred as the cyclotron line) in pulsars and the variation of its peak energy with time due to the growth of a mound on the polar cap of a neutron star due to accretion along the magnetic field lines and subsequent collapse due to instabilities. They showed that the disc flux to total flux ratio may be the parameter which determines the location of a neutron star binary in the hardness-intensity diagram. The spectra of such sources are sometimes dominated by the disc emission while in other cases the Comptonization region obscures the disc. In one source, quasi-periodic oscillations with a frequency ~kHz (kHz QPOs) were observed at energy >10 keV, for the first time, with AstroSat. They addressed a long-standing question: is the pre-burst persistent emission spectrum in such binaries non-changing and may be subtracted as background to estimate the burst spectrum? Using the larger collecting area of AstroSat-LAXPC, sufficient time resolution could be obtained which enabled the finding that persistent emission also increases during the burst, probably due to the burst mechanism causing an increase in the accretion rate.

The study of black holes, ranging from stellar mass to the massive ones seen in the centres of galaxies is an area of great interest to Indian astronomers. Several groups are involved in theoretical studies of these objects. The application of the theoretical models to explain several observational phenomenon related to accreting black holes include (a) the development of a general relativistic model of jet variability in active galactic nuclei due to orbiting blobs in helical motion along a funnel or cone shaped magnetic surface anchored to the accretion disk near the black hole, (b) development of a detailed model for an explanation of the tidal disruption events (TDEs), constructed using stellar dynamical and gas dynamical inputs that include black hole mass, specific orbital energy and angular momentum, star mass and radius, and the pericenter of the star orbit, and (c) development of theoretical models for light curves of X-ray binaries to investigate the changes in the light from such systems, by taking into consideration the self-rotation and tidal effects due to the presence of the secondary component.

AstroSat-LAXPC has been used to detect X-ray pulsations in multiple Be/X-ray binaries at hard X-ray energies for the first time. Broadband X-ray spectra in the 0.7-20 keV range, obtained using AstroSat's SXT and LAXPC, of multiple black hole X-ray binaries were fitted to extract the nature of the disc emission and other parameters such as the inner radius of the disc, accretion disc, and BH spin. Another X-ray binary was observed during a transition of spectral state accompanied by an increase in radio emission, as has been observed in similar sources before, which indicates a connection between emergence of radio jet and the change in accretion disc structure. Spin phase dependence of X-ray polarisation in Crab Nebula was detected and studied for the first time using AstroSat-CZTI.

Indian astronomers, in collaboration with an international team, have demonstrated that certain spectral and emission features of a large sample of BH X-ray binaries are significantly different from that of the neutron star binaries. The above observation showed that the BH systems behave differently from those containing neutron stars, and argued that the difference is due to the latter having a solid surface as opposed to an event horizon in the former. While existence of BHs has been proven beyond reasonable doubt, clear signature of an event horizon has been elusive, and the above work may finally provide the much-awaited purely data driven proof of its existence.

The possibility of accreting primordial black holes as the source of heating for the collapsing gas in the context of the direct collapse black hole scenario for the formation of super-massive black holes at high redshifts ($z \sim 6 - 7$) was explored. It was shown that primordial black holes with masses greater than $10^{-2} M_{\odot}$ can heat collapsing gas to an extent that H_2 formation is inhibited.

4.1.15 Active Galactic Nuclei

All galaxies have a SMBH at their center. In a few percent of the galaxies, the SMBH is accreting mass from its surroundings at a very high rate, and part of the gravitational energy released by the accreted matter is radiated causing the center of these galaxies to be extremely luminous. These are called active galactic nuclei (AGN). The X-ray spectra of AGN have been characterized in detail by Indian astrophysicists to identify the emission mechanisms responsible for various components in it. They were involved in the discovery of the so-called “soft X-ray excess” in the power-law X-ray spectrum of Seyfert galaxies and have investigated its physical origin using both spectral analysis and flux variability. Evidence for reprocessing of coronal X-ray emission in the accretion disk of AGN, which generates additional optical and UV emission from the disk, were provided via X-ray/UV/optical correlation time delay observations. AGN feedback, i.e., how the AGN emission and outflow affect their surroundings is another area studied using X-ray and radio observations of AGN and the intergalactic medium, together with theoretical cosmological simulations. In the very early days of AGN feedback related science, observation and dynamics of the evacuation of the interstellar medium in an AGN host galaxy and its effect on the AGN itself were discussed. Indian astronomers have made important contributions in understanding the radio emission from AGN. In particular, original contributions were made in morphological classification, orientation dependent unification of AGN, evolutionary scheme of AGN, dual or binary AGN, radio jet interactions with the ambient medium, luminosity function and their redshift evolution. GMRT is also playing a very crucial role in detecting cold gas around AGN and very large radio sources extending upto mega-parsec scales, and in quantifying past activities of AGN through the detection of double -double radio galaxies.

Blazars are AGNs containing a prominent jet pointing towards our line of sight. The jet emission is relativistically beamed in the observer's frame and, therefore the observed emission from the blazars is dominated by that from the jet. Hence, blazars are excellent laboratories to study the structure and properties of relativistic jets including synchrotron and inverse-Compton processes and acceleration of particles to GeV-TeV energies. Indian astronomers have contributed substantially to the characterization of intraday variability (IDV) of blazar emission, and have discovered quasiperiodicity in some of those cases. The fast variability is useful in constraining the size of the emission region. It has been shown that IDV is more common in high synchrotron peaked blazars, and such short timescale variability is highly correlated at soft and hard X-ray bands. Various groups have theoretically modelled the spectral energy distribution (SED) of blazars. Fitting the models with observed SEDs, magnetic field and energy distribution of emitting particles have been estimated, and the emitting particles have been constrained to be leptonic. It has also been shown that the flux distribution of several blazars is log-normal, which implies that some form of a multiplicative process drives the jet emission. AstroSat's SXT and UVIT telecopes are carrying out multi-wavelength studies of several Seyfert galaxies and blazars. In a Seyfert known as IC 4329A, the variability amplitude is larger in the UV band than in the X–ray bands thus suggesting that UV emission from the accretion disk is the primary driver producing X-rays via thermal Comptonization. A blazar, known as OJ 287 (believed to contain a binary system of SMBH), is being tracked extensively with AstroSat to study its different flux states tracing its spectral evolution on time scales of years and months.

In the 1990s, using EGRET observations, it was suggested that the extragalactic diffuse γ-ray emission is due to unresolved blazars. The properties of the Galactic and extragalactic diffuse γ-ray emission were characterised. γ-ray emission from normal galaxies in the local group were studied to constrain the cosmic ray energy density in those galaxies.

4.1.16 Gravitational Waves

Gravitational waves (GWs) were predicted by Einstein's general theory of relativity. It was known even then that these will be very difficult to detect, though efforts to do so were started in 1950s. An indirect confirmation of gravitational waves was observed in the change of orbital parameters of a pulsar in a binary system: this change occurs due to emission of gravitational waves. International effort to observe gravitational waves using L-shaped interferometers gained momentum in 1990s and first detection of signal was made in 2015. Gravitational waves from astrophysical events create extremely weak signals, even in the present kilometre-scale state-of-the-art detectors. The signal is buried deep in noise and sophisticated analysis strategies, based on advanced mathematical techniques, are used to detect the signal. Indian scientists have played leading roles in establishing and advancing these techniques. Very detailed analytical calculations to predict the expected waveform from an inspiralling binary of compact objects have been developed and improved over the last four decades. Indian researchers are involved in frontier research in Numerical Relativity to model these waveforms using supercomputers. Development of large computing facilities is also ramping up in the country for these purposes. GW observations provide a robust way to test Einstein's theory of General Relativity in the strong field regime, near black holes. Indian researchers have significantly contributed to develop schemes to conduct these tests, which will become far more accurate as the sensitivities of the detectors improve and space-based detectors are launched. In view of LIGO-India, huge amount of activities have started in the country in instrumentation and detector characterisation for GW observatories.

Gravitational waves in a binary merger can, in principle, arise from the merger of a wide variety of components and it takes a number of parameters to completely specify such a system. Binary systems containing a neutron star, or core-collapses of massive stars, are expected to be associated with transient like gamma-ray bursts, kilonovae, and supernovae. The search for these electromagnetic (EM) counterparts poses both observational and data-analysis challenges. Large regions of the sky need to be covered for these searches, that require the removal of contaminating transients not related to the gravitational-wave source for the identification of the unique transient counterpart. Indian scientists have contributed crucial ideas to optimize this search and also implemented these ideas in programs that have been used by international collaborations. As members of global collaborations engaged in the search for EM counterparts, scientists from India contributed to the observations of the first (and only) EM counterpart detected for a GW source – GW 170817, that was a result of a binary neutron star merger. The observations using the GMRT, in particular, were crucial in confirming some of the models proposed to explain the nature and evolution of the kilonova associated with this merger event, also observed as a short duration GRB.

4.2 Observing Facilities

This section summarises the present status and future proposed upgrades of the various operating astronomical facilities in the country.

4.2.1 Radio Astronomy

At present India has some very good facilities specialising in low frequency radio astronomy. Perhaps the oldest of these is the Ooty Radio Telescope (ORT), operational since 1970, which is a large cylindrical paraboloid 500-meter long operating at a frequency of 325 MHz. The ORT, built and operated by NCRA, the radio astronomy group of TIFR, has been used extensively over five decades for a range of studies covering interplanetary medium and space weather, pulsars, interstellar medium, extragalactic astronomy and cosmology. The ORT is currently undergoing a major receiver upgrade, which will result in a new system called the Ooty Wide Field Array (OWFA). The OWFA is designed to function as a 264-element interferometric array, and to provide a significantly larger instantaneous bandwidth as well as field-of-view compared to the legacy ORT receiver system. In addition to significantly enhancing ORT's

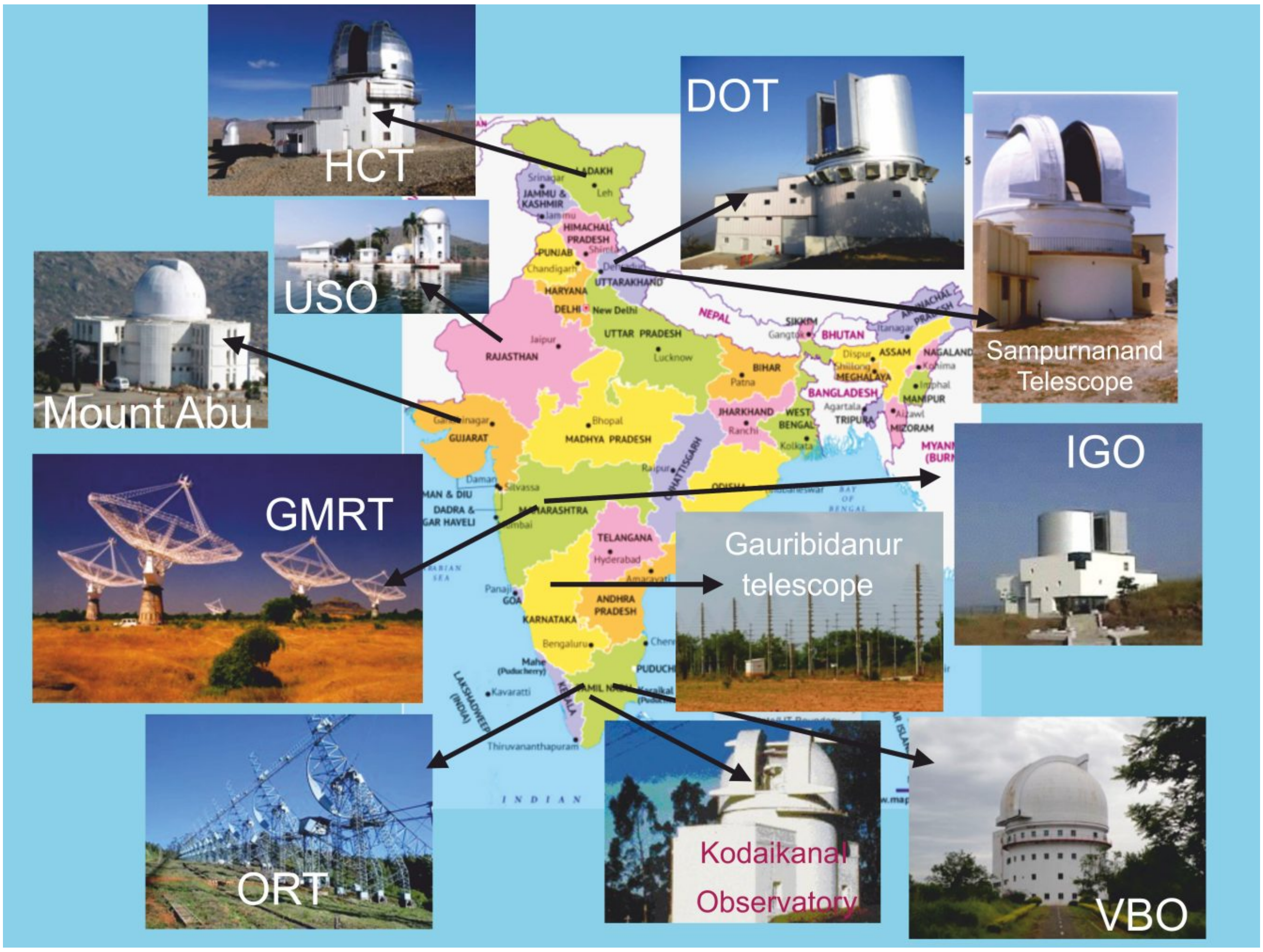

Figure 8: *Radio, optical and NIR facilities presently operational in the country.*

capabilities for heliospheric studies, this upgrade is also expected to open other avenues of research particularly in the newly emerging areas of 21-cm intensity mapping and studies of transient radio sources. *The larger field of view for OWFA along with a flexible and high time resolution data collection permits a comprehensive search for transients.*

The Gauribidanur Observatory, located about 100 km from Bengaluru and jointly operated by the Raman Research Institute (RRI) and the Indian institute of Astrophysics (IIA) hosts two low frequency radio astronomy facilities. The first of these is the decametre wave facility, the GeeTee radio telescope that operates at 34.5 MHz and is an array of 1000 dipoles arranged in a 'T' configuration, with a 1.4 km East-West arm and a 0.5 km South arm. Operational since 1976, it has been used for studies of the Sun, pulsars in our Galaxy, radio recombination lines and an all sky survey at 34.5 MHz. Since 1997, a second facility has been operational by the IIA – the Gauribidanur Radio Heliograph. This is an array of 384 log-periodic dipoles operating in the frequency range of 40 - 150 MHz to obtain two dimensional images of the solar corona.

On a larger scale, the Giant Metrewave Radio Telescope (GMRT), built and operated by NCRA, is one of the largest and most sensitive low frequency radio observatories in the world. Commissioned in 2002, the GMRT is an array of 30 antennas, each of 45 m diameter, spread out over a region of about 30 km diameter, centred at Khodad which is about 80 km from Pune. It operates in a set of frequency bands in the range 110 MHz to 1450 MHz, and supports both an interferometric aperture synthesis mode and a phased array beamformer mode, that can also be used simultaneously. Following the recently completed upgrade in 2019, the GMRT now provides almost seamless frequency coverage from 110 MHz to 1450 MHz, with a maximum instantaneous bandwidth of 400 MHz, offering an increase in sensitivity of three times over the original legacy GMRT.

Since it was commissioned, the GMRT has been used by astronomers from more than 40 countries, for a large and diverse range of studies. Every year more than 150 observing proposals are received, involving more than 500 astronomers. About half of the principal investigators for GMRT proposals are from within India while the remaining are from overseas. Over the last 10 years, the average over-subscription factor for the GMRT has been around 2.0. The GMRT represents one of the finest open access research facilities in India that is much sought after by the international research community. The GMRT data archive which hosts all interferometric observations made with the GMRT since its release as a public research facility in 2002, now houses over 300 TB of data. The archive is publicly accessible through an advanced, searchable web-based interface. More than a hundred download requests are received every month and data are made available to users automatically. Hundreds of gigabytes of data are served to users via a high speed internet link.

The GMRT has provided unique contributions to the following areas: (i) statistical detection of H I emission from distant galaxies, (ii) detection of H I 21-cm absorption over a large redshift range, (iii) detection of diffuse radio emission from distant galaxy clusters, (iv) low-frequency detection of pulsars and a wide range of transient sources, (v) discovery of several largest radio sources and (vi) TGSS survey. The upgraded GMRT (uGMRT) is recognized as one of the SKA path finders and is now been part of International Pulsar Timing Array project.

In addition to the above, Indian institutions have been involved in some international projects. The RRI has participated in the construction of the MWA observatory in Australia, where the RRI team designed and developed the digital receiver system, and astronomers continue to be involved in carrying out key science experiments with the facility. More recently, India (via a set of more than 20 institutions across the country who are members of the SKA India Consortium) is also significantly involved in the upcoming Square Kilometre Array (SKA) project as described in detail in a later section.

4.2.2 Optical and Infrared Astronomy

Observations in the optical domain have traditionally been pursued in the country, and there have been several important results and discoveries made by Indian astronomers, some of which are highlighted earlier in this document.

A suite of 1–4-meter class telescopes are available in the country for observations in the optical and NIR wavelength regions. These are located at the Vainu Bappu Observatory (VBO), Kavalur and the Indian Astronomical Observatory (IAO), Hanle, operated by the IIA; the Naintal and Devasthal Observatories operated by ARIES; Gurushikhar Observatory operated by PRL and the Girawali Observatory operated by IUCAA. Together, these telescopes enable direct imaging and spectroscopic observations over the wavelength range of ~ 3700 Å to 4.0 μm, and polarimetric observations over the wavelength range of ~4000 - 9000 Å.

1-meter class telescopes: The 48-in refractor at the Rangapur observatory and the 1-meter telescopes at Kavalur and Nainital were set up in the late 1960s - early 1970s. Two decades later, the 1.2-meter telescope at Gurushikhar was set up as India's first infrared telescope. Two 1.3-meter telescopes were added in the past decade, one at Devasthal and another at Kavalur. A 0.7-meter, wide-field, robotic telescope, the GROWTH-India Telescope (GIT) was recently installed at IAO.

The 1.04-meter Sampurnanand telescope (ST) at Nainital is equipped with a CCD imager for photometry, an imaging polarimetry, a fast photometer and a low resolution spectrograph, while VBO's 1.02-meter Carl Zeiss Telescope (CZT) is equipped with a photopolarimeter and a low resolution spectrograph. The Mount Abu Gurushikhar Observatory's 1.2-meter telescope is equipped with a suite of instruments such as a two channel fast near-IR photometer for lunar occultation, fiber-linked astronomical grating spectrograph, a Fabry-Perot spectrograph, optical polarimeter, near-IR infrared camera spectrograph, and an advanced high resolution spectrograph. The two 1.3-meter telescopes at Devasthal and Kavalur are equipped with CCD imagers. The GIT offers wide field multiband imaging capabilities with a field of view of $45' \times 45'$.

The 1-meter class telescopes have contributed significantly to (i) the understanding of origin and evolution of different classes of star clusters, (ii) physics of star forming regions (iii) photometric studies of galaxies, (iv) intranight variability of different classes AGNs, (v) followup studies of nova outbursts, GRBs and other transients and (vi) observations of transiting exoplanets. The ARIES-ST observed the first ever optical counterpart detected in a GRB event in 1999. The 1-meter telescopes have also been used very effectively in the study of objects in our own solar system through occultation observations. VBO's CZT was instrumental in the discovery of atmosphere around Jupiter's moon Ganymede, and also in the discovery of rings around Uranus (in the 1970s). The GIT is dedicated for the observations of transients and is contributing significantly in the search for optical counter-parts of gravitational wave sources, optical follow-up of gamma-ray events and other fast transients, monitoring of supernovae, and observations of novae in M31.

2-meter class telescopes: The establishment of the Kavalur Observatory (later named as Vainu Bappu Observatory, VBO) led to the indigenous development of the 2.34-meter Vainu Bappu Telescope (VBT). When installed and commissioned at Kavalur in 1986, VBT was the largest optical telescope in Asia. The VBT is equipped with a suite of instruments that includes the prime focus imager at the prime focus, Cassegrain focus instruments such as a low resolution spectrograph, speckle interferometer, a fiber-linked integral field spectrograph and a prime focus fiber-fed high resolution spectrograph providing spectra at resolutions $R \sim 30000 - 60000$.

IIA established a high altitude observatory, the Indian Astronomical Observatory (IAO) in Hanle, Ladakh. IAO hosts the 2-meter Himalayan Chandra Telescope (HCT), located at an altitude of 4400m above mean sea level. The telescope has been in operation since 2000 and is a critical facility for Indian astronomers today. The telescope, dome and instruments are controlled remotely using a dedicated satellite link from IIA's CREST campus at Hosakote, Bengaluru. An instrument cube at the Cassegrain focus enables mounting of 4 instruments on the side ports, and one on the on-axis ports. The available instruments are an optical faint object spectrograph (HFOSC) for imaging and low resolution spectroscopy in the optical region, a near-Infrared spectrometer camera imaging and low resolution spectroscopy (TIRSPEC) in the near-IR regions, and a high resolution optical spectrometer (HESP) with a resolution of $R \sim 30000 - 60000$. IUCAA, Pune also installed a 2.0-meter optical and near-IR telescope at Girawali in November 2006. The telescope is equipped with a faint object spectrograph with polarimetric capabilities and a near-IR imaging camera. IUCAA has recently built an autonomous laser-adaptive-optics system for IGO called ROBO-AO. A 2.5-meter telescope was recently installed at PRL's Gurushikhar Observatory. This telescope has instruments that will enable photometry, polarimetry and low-medium and high resolution spectroscopy in the optical and near-IR wavelength regions.

The 2-meter class telescopes have proved to be the work horse instruments for optical-NIR astronomy in the country. They are used for observations of objects ranging from the nearby solar system to high redshift quasars. A few areas with significant contribution has been in (i) studies of transients such as novae, supernovae and gamma-ray burst sources, (ii) variability in stellar sources, (iii) chemical abundances in the atmospheres of stars in our Galaxy and the local neighbourhood, (iv) studies of star forming region in the Milky Way galaxy and nearby starburst galaxies, (v) time variability studies of broad absorption line quasars, (vi) intra-night variability in active galaxies, (vii) reverberation mapping studies to measure the mass of the black hole in AGNs, and (viii) estimation of H_0 using strongly lensed galaxies.

The 4-meter class telescopes: India entered the category of countries with 4-meter class telescopes in 2016 with the installation of the 3.6-meter Devasthal Optical Telescope (DOT), located at the Devasthal Observatory operated by ARIES. The DOT is currently the largest optical-IR telescope in Asia. The telescope fills a large longitudinal gap in the 4-meter class telescopes in the Asia region. The telescope is also the first of its kind in India that features an active optics system, a wavefront sensor and pneumatic actuators which compensate for small distortions in the shape of the 4.3 tonne mirror due to gravity or atmospheric aberrations. This feature enables obtaining images of the sky at sub-arcsecond spatial resolutions. The telescope is equipped with a suite of instruments, an optical CCD imager, a low resolution optical spectrograph, a near-infrared spectrograph in the 0.6-2.2 μm range and a near-IR imager in the 1-4 μm range, providing imaging and spectral capabilities in the visible and near-infrared bands.

Deeper imaging and spectroscopy in optical and NIR wavelengths of Galactic and extra-galactic point sources and objects with low surface brightness are the broad scientific objectives of the 3.6-meter DOT. It is also planned to conduct optical observations of new sources discovered using the GMRT and the AstroSat. Considering longitudinal advantage, the DOT is also well-suited for observations of many time-critical and transient events including follow-up of Gravitation-Wave sources in a larger perspective of time domain astronomy. To maintain this largest optical observing facility as a productive one during the coming decade plans are underway to upgrade the facility and equip it with new backend instruments such as a fiber-linked integral field spectrograph and a high resolution spectrograph.

Another unique facility, the 4.0-meter International Liquid Mirror Telescope (ILMT) facility, developed in collaboration with Belgium, Canada and Poland is now operational at Devasthal. The mercury mirror of the ILMT has a 4-meter diameter with an aperture of f/2 defined by the speed of rotation. The telescope is equipped with a 4Kx4K CCD camera for imaging in the 4000 to 11000 Å spectral range. Given the zenith observing mode of a liquid mirror telescope, the location of the Observatory at a latitude of $\sim 30^{0}$ N is ideal for surveying the north galactic pole. A deep (optical = 22 mag) survey will approximately cover 50 square degrees at high galactic latitudes, which is very useful for gravitational lensing studies as well as for the discovery of various classes of interesting extragalactic objects (cf. new quasars, supernovae, clusters, etc.).

Utilisation and requirement: The existing optical/IR facilities are well utilised by the community. The 1-meter telescopes at VBO and Nainital that were established in the early 1970s are still being used, as is also the 1.2-meter PRL telescope. The 2-meter HCT and the 3.6-meter DOT have around 300 users and are oversubscribed by a factor of 2-3 on an average. The HCT has proved to be a very productive telescope with over 350 refereed publications, and nearly 70 Ph.D. theses that have used data obtained with the telescope. The two 1.3-meter telescopes are being utilised very effectively in long term monitoring of AGN variability, transits of exo-planets and observations of transients, GRB sources in particular. The ARIES 1.3-meter telescope is also used for Lunar occultation observations.

All the existing facilities are yielding good science, however, the size of the telescopes limits their capability to the studies of relatively brighter, nearby sources. None of the recent facilities match the global initiatives undertaken in the past two decades. The optical-IR telescopes in India as compared to those available globally are summarised in a chronological manner in Table 1.

It is clear from the table that India is far behind the rest of the world as far as access to state-of-the-art optical astronomy facilities are concerned. Not only in terms of the telescope aperture, but also in terms of advanced technology instruments. For India, the best way to catch up with the rest of the world is to participate in existing large facility programmes, as well as in multinational efforts to build mega-facilities, and through which the necessary technical skills to create large facilities within the country, such as a 10-meter class telescope with state-of-the-art and innovative instruments, can be established.

A small fraction of Indian astronomers have access to the 12-meter Southern African Large Telescope (SALT) located in South Africa, through IUCAA, which is a partner at 6% level. Through this partnership, scientists and engineers at IUCAA are contributing to the development of new technology instruments, bringing in experience in fibre-fed instruments, in a limited way. A larger-scale, national-level participation in an existing 10-meter class telescope will bring a wider experience in the generation of globally competitive science using state-of-the-art instruments.

India is partnering to build a 30-meter telescope, the TMT. Access to the TMT will no doubt enable Indian astronomers to do cutting edge science comparable to their peers elsewhere. However, the gap between the current largest telescope (3.6-meter) and the 30-meter telescope is huge. *A 10-meter class telescope in the country is essential to effectively utilise India's share of observing nights with the TMT.* Additionally, combined with other large facilities in the country (existing and proposed) such as the GMRT, LIGO-India and space astronomy missions, a 10-meter optical-IR facility in country will enable multi-messenger, multi-wavelength astronomy that will be globally competitive.

Table 1: *A chronological summary of development of Optical-IR telescopes in India and rest of the world.*

Period	India	Global
Before 1960	—	1-5m class telescopes (USA and Europe): 1m Yerkes, 2.5m Mount-Wilson, 5.1m Hale Telescope (Palomar)
1960–1980	1m class telescopes: Japal Rangapur Obs. (1.2m:1968), UPSO-ST (1m:1972), VBO (1m:1972)	4-6m facilities: CFHT (3.6m), UKIRT(3.8m IR), 6m Russian telescope, AAT (3.9m) (USA, Europe, Australia, Canada)
1980–1990	1-2m class facilities: VBT (2.34m:1986)	4-6m class telescopes (UK, USA, Australia, Russia, Europe), Hubble Space Telescope (2.4m)
1990–2000	1-2m class facilities	8-10m class facilities: 2 Keck (USA, Canada), 4 VLTs (EU), Gemini South, North (USA, Canada, Chile, Brazil, UK, Argentina, Australia)
2000–2010	1-2m class facilities: HCT (2m:2000), IGO (2m:2005)	More 8-10m telescopes: 8m Subaru (Japan), 10m HET (USA, Germany), 11m SALT (South Africa, USA, Europe, India), 10m GTC (USA, Spain, Mexico, ESO)
2010–2020	2-4m class facilities: HCT, 3.6m Devasthal Optical Telescope (DOT:2014)	8-10m class telescopes, Network of 1m class telescopes dedicated for transient surveys and follow-up, 8m wide-field survey telescope (Vera C.Rubin - LSST)
2020–2040	2-4m class facilities: PRL 2.5m(2022), 4m ILMT (2022)	10m Mauna Kea Spectroscopic Explorer, 25-40m telescope facilities: GMT (25m) (USA, Australia, South Korea), TMT (30m) (USA, Canada, Japan, India, China) and EELT (39m) (14 European countries - ESO).

4.2.3 TIFR Balloon Facility

Since 1998, the TIFR 100-cm balloon-borne telescope and the Japanese Fabry-Perot single-pixel spectrometer (Spectral Resolution 2000) as part of the TIFR-Japan collaboration have contributed significantly in the field of far-IR astronomy and star formation. The far-IR [CII] line at 158 m is the best tracer of star-forming molecular clouds. To investigate the role of cloud-cloud collision in high-mass star formation, this facility offers an excellent platform with relatively high spectral resolution observations of the [CII] line velocities of putative colliding clouds. To cover a typical star-forming region in our Galaxy, one requires high speed of spectral mapping. Among the existing astronomical observational facilities in the world, only balloon telescopes can realize both relatively reasonable spectral/spatial resolution and sufficiently large area [CII] observations. Several balloon flights have been launched since 1998 with the latest being the past three consecutive campaigns (2017-2019). The Japanese team is now developing a new [CII] spectrometer which has spectral resolution 5 times higher than the current spectrometer and a 5x5 new array detector replacing a single pixel detector. The former would enable us to measure the difference in the velocities of the associated clouds, while the latter is to spatially resolve the filamentary structure through the deconvolution technique.

The spectrometer will be installed in the balloon-borne telescope system after refurbishing the system and checking its interface with the instrument. This experiment will be carried out from TIFR National Balloon Facility at Hyderabad which offers a unique blend of expertise attained over decades of successful balloon experiments in the frontiers of Astronomy, Astrobiology, High Energy Physics and Atmospheric Sciences. These indigenous facilities have led to many PhDs in Astronomy and also helped train many engineers in world class technology. The TIFR Balloon Facility is also involved in many of the test programmes of ISRO for space qualification of modules to be used in future satellites. This facility can also be used for the development of any space-based astronomy payloads.

4.2.4 X-ray and UV Astronomy from Space

There have been several small payloads, particularly in the X-ray wavebands, that have been launched using ISRO's satellites. These payloads were launched for a few, very specific experiments, with short lifetimes.

AstroSat, India's first observatory class satellite dedicated for Astronomy was launched in 2015. AstroSat is capable of simultaneous measurements in a broad energy band from far Ultra-violet to high energy X-rays with the help of four co-aligned scientific payloads. designed and developed by multiple research institutes from India in collaboration with ISRO centers. The hard X-ray and the soft X-ray payloads (LAXPC, CZTI, SXT) and the UV imaging telescope (UVIT) were realized by the Tata Institute of Fundamental Research, Mumbai, the Indian Institute of Astrophysics, Bengaluru and the Inter-University Center of Astronomy and Astrophysics, Pune, in collaboration with the Center for Space Astronomy, Canada and the University of Leicester, UK. The fifth payload, the Scanning Sky Monitor was built by the Indian Space Research Organisation. AstroSat has recently completed eight years of its designed life and continues to produce data of high quality. Although initially envisaged as a 5-year mission, this space observatory is expected to be in operation for a few more years to come.

AstroSat is operated as a proposal based observatory and the observation time is open to astronomy community of the entire world. Currently, AstroSat is serving close to 1500 registered users from 48 countries. In addition to simultaneous measurements over a broad energy range, AstroSat has other unique capabilities like the highest angular resolution in UV over a large field of view of 28 arcmin, largest collecting area in medium energy X-rays, X-ray polarisation measurement capability in hard X-rays for bright sources to name a few. With these unique capabilities, combined with simultaneous measurement capability, AstroSat has produced several interesting results. AstroSat is successfully being used to study star clusters, star formation in galaxies, accretion processes in binaries, supernova remnants, outbursts of novae and peculiar transients, X-ray polarisation in GRBs, active galactic nuclei and blazars and galaxy clusters.

AstroSat data are archived and made available to the scientific community at large, allowing for production of science results beyond the original goals. These data will continue to be of immense use to the global scientific community even beyond the lifetime of the mission.

The recent launch of XPoSat with the X-ray polarimeter, Polix, has opened up a new, emerging area of X-ray polarimetry. Polix is the second such facility available globally.

4.2.5 Ground Based High Energy Experiments

For the very high energy γ-rays and cosmic rays India has developed and used several facilities over the years: Pachmarhi Array of Cherenkov Telescopes (PACT) from 2000-2011, High Altitude Gamma-ray ARray (HAGAR) telescope array at Hanle in the Ladakh region of Himalayas, and TACTIC at Mt. Abu. HAGAR is the first phase of HIGRO (Himalayan Gamma-Ray Observatory) collaboration comprising BARC, TIFR, IIA and SINP. A large area imaging Cherenkov telescope MACE (Major Atmospheric Cherenkov Experiment) is setup, as a second phase of HIGRO at Hanle. This telescope, having 21-m diameter, is the world's third largest imaging telescope with a very low threshold of 30 GeV. MACE-I is now in operation, and MACE-II is under development.

4.2.6 Solar Facilities

The ground based observing facilities available for the observations of the Sun include those at the Kodaikanal Solar Observatory (IIA), the Udaipur Solar Observatory (PRL), the Gauribidanur Radio Observatory (IIA and RRI) and the solar telescope at ARIES, Nainital.

The Kodaikanal Observatory was established in 1899 as a Solar Physics Observatory and has the following facilities:

- A Solar Tower Telescope consisting of 60-cm diameter two-mirror fused quartz coelostat mounted on a 11-m tower platform that directs sunlight via a flat mirror into a 60-m long underground horizontal 'tunnel'. This telescope is equipped with a 38-cm aperture f/90 achromat for obtaining solar images, and also a Littrow-type spectrograph and a dual spectropolarimeter.

- A dual-channel full disk solar imaging telescope White light Active Region Monitor (WARM), consisting of a two-mirror coelostat. The telescope along with additional optics produces two images in perpendicular directions, in the photospheric 430.54 nm line, and the chromospheric 393.3nm line.

- A 20-cm refractor, operated in the Hα wavelength. The telescope can be operated in two modes, (a) full disc mode with spatial resolution of 1.24"/pixel and (b) partial disc or high resolution mode with 0.49"/pixel.

The Udaipur Solar Observatory (USO) located on an island in the middle of lake Fathesagar in Udaipur provides excellent conditions for observations of the Sun. There are two main instruments operating at the observatory:

- The Multi-Application Solar Telescope (MAST), an off-axis Gregorian afocal telescope with a clear aperture of 50-cm with a field de-rotator to compensate the image rotation and a guider to track the Sun continuously. It also has a wave front sensor for correcting optical misalignments caused due to temperature variations. The potential of the MAST is realised through specialised back-end instruments, a narrow–band imager to record simultaneous images of the photosphere and chromosphere, a polarimeter to measure the magnetic fields in sunspots and an adaptive optics system for image stabilisation and to achieve diffraction-limited performance.

- The Global Oscillation Network Group (GONG) instrument that is part of a community-based international programme to conduct a detailed study of solar internal structure and dynamics using helioseismology. USO is one of the sites of the six-station network of extremely sensitive, and stable velocity imagers located around the Earth to obtain nearly continuous observations of the Sun's "five-minute" oscillations, or pulsations.

Gauribidanur Radio Observatory was established in 1976 and is used primarily for observations of the Sun in the decameter wave radio region. The observatory consists of:

- A decametre wave radio telescope (GEETEE) consisting of 1000 dipoles arranged in a 'T' configuration, with a 1.4 km East-West arm and a 0.5 km South arm. It has been engaged in the study of radio waves at 34.5 MHz emanating from Sun and various other diverse objects in the sky. This facility provided the first two-dimensional images of radio emission from slowly varying discrete sources in the outer solar corona.

- A radioheliograph (GRAPH) to obtain two dimensional images of the solar corona simultaneously at different frequencies in the range 40 - 150 MHz. The frequency coverage of GRAPH is unique that it provides useful information on the solar corona in the height range 0.2 - 0.8 Rs above the solar surface (Rs = radius of the Sun), which at present is difficult to observe at other frequencies in the electromagnetic spectrum. No other radio telescope, dedicated for solar observations, is presently operational in the above frequency range anywhere in the world.

- A high resolution radio spectrograph (GLOSS) that is used in conjunction with the GRAPH for obtaining dynamic spectrum of the transient emission from the solar corona. The GLOSS and the GRAPH together provide spectral and positional information on eruptive solar activity, again a unique combination.

- The Gauribidanur Radio Interferometric Polarimeter (GRIP) is an east-west one-dimensional array of 40 log periodic dipoles set up to probe the coronal magnetic field in the height range 0.2 - 0.8 Rs, above the solar surface.

Space Instruments: In the context of space based observations of the Sun, Aditya-L1 space mission, launched in September 2023 is the first national initiative to observe the Sun from space and characterize our space environment. The Aditya-L1 mission was jointly developed by the Indian Space Research Organisation (ISRO) and several Indian academic organisations around the country including IIA, PRL, VSSC (ISRO), IUCAA and IISER-Kolkata. Aditya-L1 will observe the Sun's atmospheric dynamics and the genesis of solar magnetic storms and track the propagation of these storms close to the Sun. In-situ instruments will also characterize the near-Earth solar plasma wind properties such as particle and magnetic fluxes that determine Earth's space environment.

While India has a century-long history of ground-based optical observations of the Sun, no large solar-telescope facility has been created in the modern era to match global initiatives. It is imperative to establish a large (2-meter class) ground based solar telescope in the country.

4.3 Enhancing the Utilisation of Existing Facilities

As discussed in the previous sections, the Indian astronomical community is operating several observing facilities having different kinds of instruments for decades. We expect these observatories to be operational even in the era of future large facilities. As the Indian astronomy community is embarking on different mega science programmes it is important that the existing observatories and instruments are maintained and upgraded efficiently to cater to the needs of the community at any given time. It is also important that an efficient use is made of the facilities. Below we provide possible suggestions that we believe will enable efficient use of the facilities as well as provide ample resources for the growth of the community.

- **Observatory Upgrades:** In order for the existing observatories to have relevance in the coming decade it is important to have clear upgrade plans (for telescopes as well as associated instruments) for the future. In the case of optical astronomy, many of the telescopes are decades old and require suitable upgrades to increase their efficiency and use in an automated manner. The upgrades should also include instrumentation such as wide field imaging and spectroscopic capabilities and adaptive optics imaging and spectroscopic capabilities. As the user pool of different observatories are the same, it will be more efficient and productive if different institutions coordinate with each other to reach a global road map for instrumentation. This will ensure that a wide range of instruments are available to the Indian astronomers instead of having the same kind of instruments in all the facilities.

- **Common Time Allocation Committee:** At present, each individual observatory allocates observing time through a proper review process overseen by a Time Allocation Committee (TAC). Usually, each proposal is reviewed by one or two external experts and the time allocation happens twice or thrice a year. It is well documented that the same set of proposals are submitted to the various facilities, and the evaluation process is somewhat repeated several times. The efficiency of the TAC process and utilisation of different telescopes can be improved with a common, national-level time allocation committee that can oversee the allocations of observing time on various observing facilities in the country. The efforts of the host institution in setting up, operating and maintaining these facilities needs to be duly recognised, and this can be in the form of host institutes retaining a good percentage of the telescope time for themselves and releasing the remaining fraction to the national pool. Astronomers from the host institutes should be eligible for competing for the national time too. The constitution and terms of reference for this national TAC can be decided by a joint committee of the institutes hosting different observing facilities.

- **Common Pool of Technical Resources:** At present each observing facility has its own technical staff to run and maintain the telescopes and associated instruments. It is difficult to keep a large pool of well trained engineers and technical people as they find good opportunities with better salaries in the industries. It will be good to have a centralised repository of technical staff with expertise to attend to specific issues for various telescopes. As an example, coating of all the primary mirrors can be carried out by a single team. In order for such an arrangement to work it is important to have good coordination between different observatories.

- **Unified Database:** It is now well documented that the scientific outputs from facilities like HST, SDSS, and those at ESO have seen a manifold increase from the usage of archival data. In particular, availability of raw data and pipeline data reduction tools that will produce uniform quality processed data have played a major role. Uniform format data from all the facilities is highly desirable for an efficient use of multi-facility data. Therefore, it is recommended to have a centralised data archive facility, managing data taken from various astronomical facilities in the country. A unified search engine to search the multi-wavelength database for a given target should also developed.

- **Multi-wavelength Multi-messenger Networks:** Astronomy of transients of various kinds will be an important area in the coming decade. In particular, due to its geographical advantages, Indian observatories will play an important role in monitoring and locating some of the important and interesting transients. It is now well demonstrated that being part of international network equipped with necessary tools to respond to transient triggers quickly is absolutely essential. Therefore it is important to consider (i) forming a network of various existing Indian facilities (in ground as well as space covering multi-wavelength) and (ii) being connected to international networks. It is also recommended to have spectroscopic facilities (in 4 to 10-meter class telescopes) to be able to classify some of interesting transients that are bright when visible to our observatories.

- **A Consortium of Observatories:** Countries like the USA (NOAO, NRAO), Japan (NAOJ) and China (NAOC) have an umbrella organisation that operates a set of observatories, enabling the national community to have access to the best facilities. In India, at present, the observing facilities are operated by individual institutes that set up the facility. Although, in general, these facilities are open to the entire national community, a centralised structure will allow implementation of the suggestions above in an efficient manner. In future, the use of megascience facilities, both national and international requires a national level coordination. The setting up of a consortium leading to a virtual national optical observatory could be explored by the various organisations through a proper MOU among institutes running different observatories in the country. This consortium can then enable networking of the facilities, manage the common pool of observing time, consolidate technical resources, etc. In this way, we will be able to get the benefits of both approaches highlighted above.

- **Developing and Preserving Astronomy Sites:** As mentioned earlier in this document, our observatories are spread across the nation. These observatories, when set up, were isolated, located at fairly remote sites with minimal population and pollution. However, over the years, with advancement and increasing population, the sites have degraded. Light pollution severely hampers observations of faint astronomical sources from these sites. General increase in the pollution causes increase in the aerosol content, leading to more atmospheric extinction in the blue wavelength regions. In addition, monsoon effectively shuts down all observatories for nearly 3-4 months. The only region in India that still remains less populated and less polluted is Ladakh. Hanle has proved to be quite a stable site over the past two decades, and is also not as severely affected by the monsoon as other observatories. Site surveys have shown the Ladakh region to have excellent sites for solar astronomy and multi-wavelength night time astronomy. It is thus imperative to preserve the dark skies of Ladakh. As a first effort, the region around the IAO at Hanle has been identified as a dark sky reserve by the State. This dark sky reserve will not only help scientific endeavour, but will also promote astro-tourism in the region, providing a source of income to the local population.

  Like the need for dark skies for optical astronomy, there is a strong need for “quiet skies” in the radio region. Man made radio noise prevents detection of the weak radio signals from astronomical sources. It is therefore important to have pockets of radio quiet areas that will enable astronomical observations. The region around GMRT is already protected, and it is important to identify and protect sites of future facilities.

  It is important for India to join forces with the IAU, UNESCO and other international bodies for the protection of dark and quiet skies.

- **International Consortia of Observatories:** To enable access to a wide variety of telescopes and instruments, several countries have jointly set up consortia of observatories. For example, East Asian Core Observatories Association (EACOA) was constituted between National Astronomical Observatories of Chinese Academy of Sciences (NAOC), Korea Astronomy and Space Science Institute (KASI), Academia Sinica Institute of Astronomy and Astrophysics (ASIAA, Taiwan), and the National Astronomical Observatory of Japan (NAOJ). These institutions share some fraction of observing time on their facilities. Similarly efforts are on to create network of telescopes owned by the BRICS partner countries. Being part of such international networks will be highly beneficial for the growth of our community.

5 MEGA SCIENCE PROJECTS IN ASTRONOMY - PRESENT AND FUTURE

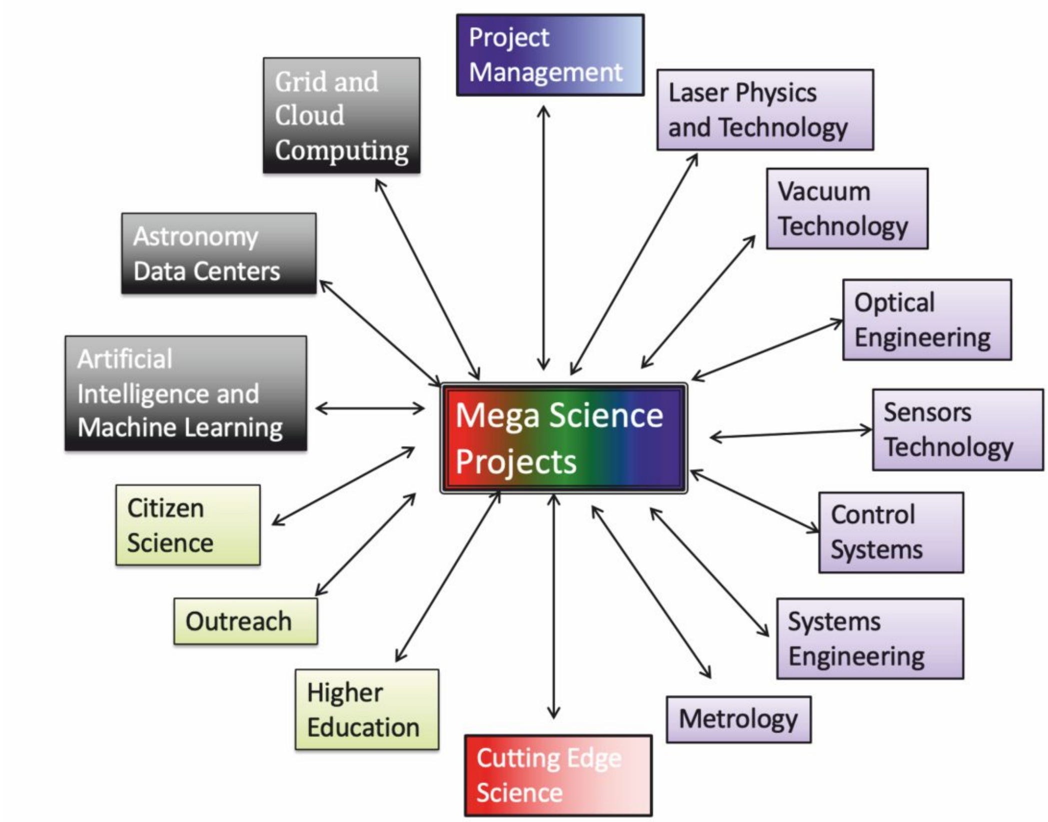

Figure 9: *Cartoon depicting the importance of handshake between various aspects of management, science & technology and education and public outreach for successful execution of a Mega Science Project.*

It is well recognised now that to address the scientific questions highlighted in Section 2, we need to have large (mega) science facilities. As illustrated in Figure 9 a typical mega science project requires expertise from a wide range of Science & Technology areas. The technical and monetary requirements are huge and such facilities can be envisaged only through large and often international and multi-institutional collaborations. Therefore, participating in a mega science project not only allows Indian astronomy community to perform top-end research at par with best in the world, but also allows the community (both scientists and industrial partners) to develop and/or acquire very high-end technology. Success of a mega project also depends strongly on the community development and how the project is managed. This Section summarises the various mega science projects at both international and national levels the Indian astronomy community is already engaged in and/or aspires to pursue in the near future.

5.1 Mega Projects where India is already a Partner

To begin with, we summarise the status of various upcoming Mega Science Projects in A&A in which Indian astronomers are involved.

Figure 10: *Artistic impressions of the three Mega Science Projects in A&A in which Indian astronomers are involved.*

5.1.1 Thirty Meter Telescope

The Thirty Meter Telescope (TMT) will be one of the three world's most advanced ground-based observatories that will operate in optical and mid-infrared wavelengths. It will be equipped with the latest innovations in precision control, phased array of mirror segments and laser guide star assisted adaptive optics system. At the heart of the telescope is the segmented mirror, made up of 492 individual hexagonal segments, each 1.44-m in size. Precisely aligned, these segments will work as a single reflective surface of 30-m diameter. TMT is an international partnership between Caltech and the Universities of California in the U.S.A, Japan, Canada, China and India. India is a 10% partner, through the DST and DAE. Seventy percent of India's in-kind contribution, is by way of supply of specific hardware and software components. ARIES, IIA and IUCAA are the three main institutes spearheading the efforts of India-TMT, with TIFR as an associate. The activities of India-TMT are coordinated by the India-TMT Coordination Center (ITCC) set up at IIA, which is the nodal institution.

The key science goals of TMT range from understanding the distant, very early Universe to the study of our solar system objects. These include understanding the nature of dark energy and dark matter, formation of the first stars and galaxies, black holes and extreme physics through the study of transients, study of exoplanets and search for signatures of extraterrestrial life. When built, TMT will produce breakthroughs across a wide range of scientific topics, ensuring a generational legacy of discovery with leadership in optical/infrared astronomy for the TMT partners. TMT will provide an unparalleled view of the Northern Sky and all its unique astronomical targets.

India has been a member of the TMT project since 2010, initially as an Observer, and as a partner since December 2014. India-TMT has the core responsibility of providing various sub-systems of the project as our in-kind contribution. This includes hardware for the primary mirror (M1) control system consisting of 3234 edge sensors and 1476 actuators, the segment support assemblies for all 594 segments, 82 polished primary mirror segments, mirror coating vacuum chambers, part of observatory and telescope control software and contribution to the development of first light and second generation instruments. To realise India's contribution of the 82 polished segments, a large Optics Fabrication Facility (ITOFF) is established in IIA-CREST, Hosakote, Bengaluru. This national facility is a one-of-its-kind facility for polishing large optics in the country. Several astronomers from Indian research institutes and universities are members of the TMT International Science Development Teams and are contributing to the development of detailed science cases and key observational programmes, and drawing up the science requirements for future instruments and upgrades.

The project has completed the design of the telescope optics, structure and dome, as well as the various control systems and software requirements and has now entered the Construction Phase. To fulfil the science goals, ten science instruments and an adaptive optics system have been proposed. Of these, three instruments and the adaptive optics system will be available at first light. The first light instruments are in the final design stages. The availability of the remaining 7 instruments is staggered, with two new instruments coming online every five years. In line with this schedule, the concept design phase for the next set of instruments is already underway. India-led proposal for a second generation instrument, a multi-object high resolution spectrometer (HROS), was rated as one of the high-priority instruments.

ITCC is working with several Indian industries for the fabrication of edge sensors, actuators and the segment support assemblies. Actuator prototypes supplied have successfully completed the life cycle and environment tests. New techniques are being developed for coating and etching the edge sensors. The concept design of the coating chamber for secondary and tertiary mirrors has been completed. While the technology for polishing the aspheric mirror segments has been acquired via technology transfer from a foreign industry, the technology for precision glass cutting for hexing and pocketing the segments is being developed by an Indian MSME. The Common Software (CSW) which forms the main backbone skeletal communication system of the whole TMT software architecture has been successfully developed. Development of specific modules of the Telescope Control Software (TCS) is also under progress. In addition, Indian astronomers and engineers are also involved collaboratively with other aspects of the observatory development such as management, systems engineering, the telescope optics alignment and phasing system (APS), instrument development (first light and second generation) and other areas of scientific leadership. This includes core involvement in the first light optical instrument WFOS, for mechanical design of the grating exchanger and camera articulation system, development of the physical model of the instrument based on the optics design to evaluate parameters such as flexure, field distortion etc. and development of the instrument control software. Preliminary design and analysis of the optics for the India-led HROS and generation of an infrared guide star catalog are also under progress. All the above activities are providing valuable experience to scientists, engineers and industries in the country that will enable the community to build a national large segmented mirror telescope and the required high precision instruments including adaptive optics.

5.1.2 Square Kilometer Array

In the domain of radio astronomy, India is actively involved in the Square Kilometer Array (SKA) project, which is a state-of-the-art, global project that aims to build the biggest and most sensitive radio telescope, for addressing a wide range of cutting-edge science goals. The observatory will be co-located in Australia and South Africa, with operational headquarters in the United Kingdom. At present, 12 nations are participating in this Mega Science Project that is expected to revolutionise radio astronomy, while driving the growth of many important new state-of-the-art technologies. The project has completed the detailed design of SKA Phase-1, and has entered the Construction of this phase, with 2027 as the target date of completion and transitioning into full-fledged operations stage, with execution of key science projects commencing around 2029. Participation from industry on a large scale has been, and will be, an important ingredient in the design and construction of the SKA.

The SKA Phase-1 observatory consists of two telescopes, SKA-Low (in Australia) and SKA-mid (in South Africa). The SKA-Low is an array of dipole antenna stations designed to cover the frequency range from 50 to 350 MHz. The 512 stations will be arranged in a large core with three spiral arms, spread over a distance of 65 km. Each station will contain 256 dipole antennas, with highly flexible arrangements for forming multiple beams for various applications. The SKA-mid will consist of an array of about 200 offset Gregorian dish antennas, with receivers designed to cover the frequency range 350 MHz to 14 GHz. Most of the dishes will be concentrated in a core, with three spiral arms extending over 150 km. High capacity optical fibre systems, sophisticated digital signal processing hardware, super-computing capabilities for real-time generation of images and other data products, and a complex end-to-end observatory management system are some of the other key technology elements of the SKA Phase-1.

The key science goals of the SKA Phase-1 have a very wide scope covering areas such as (1) strong-field tests of gravity using pulsars and black holes (2) origin and evolution of cosmic magnetism (3) Cosmic dawn and the epoch of reionisation, and (4) cradle of life and astrobiology. India has been an active member of the SKA initiative since its early days (2010 onwards). India has played an important role during the Design Phase of the SKA, where a team from NCRA along with industry partners, led the design effort from initial concept to the successful final critical design review for the Telescope Manager (TM) System of the SKA Phase-1 – the end-to-end observatory management system that will be the brain and nerve centre of the entire, distributed observatory. India also participated in the design of the Pulsar Search System (PSS) and the Signal and Data Transport System for SKA Phase-1. Along with this, the Indian community has made significant contributions in several areas of SKA science through theoretical developments, computer simulations and observations with SKA pathfinder and precursor facilities, and has a well defined science case developed for using the SKA in the future.

Currently, India is engaged in the Early Prototyping Phase of the work, while preparing for the Main Construction Phase of SKA. This includes the development and delivery of early prototype modules of the TM System and the PSS, and also work on understanding the early prototypes for the SKA-Low station digital processing units. During the Construction Phase, India will be involved in the SKA in 4 different areas : (i) as the Tier-1 lead country in the delivery of the Observatory Management System (a scope-enhanced version of the TM System) (ii) as a major partner in the construction and delivery of the station digital hardware and firmware for SKA-Low (iii) as a contributor to the final PSS system and (iv) as a contributor to the Band-1 receiver system for the SKA-Mid. In addition, India will host one of the SKA Phase-1 Regional Data Centres, allowing priority access to SKA data of interest to the Indian astronomy community, including supporting the execution of post-processing pipelines.

5.1.3 LIGO-India

The detection of Gravitational Waves (GW) by the Laser Interferometer Gravitational-wave Observatory (LIGO) in 2015 opened a new era in Astronomy. At present GW from ninety mergers of compact binary stars have been detected. The field is however nascent and enormous scope for scientific discoveries lies in front of us. While the parameters and characteristics of the detected binaries (mass, spin, precession, and properties of dense nuclear matter) sample a wide range, a large number of detections will be necessary to get a concrete idea about the statistical distribution of these astrophysical parameters. This will, in turn, help us understand the origin and characteristics of these exotic objects, shine light on the evolution of the universe and perform a strong test of Einstein's General Theory of Relativity. In addition, there could be unexpected sources that could bring fundamental changes in our understanding of the universe. In the next few years, the upgraded network of detectors, which will include LIGO-India bringing in much larger network baselines, is expected to provide crucial information to address these astrophysical questions of profound interest.

LIGO-India is a planned world-class multi-disciplinary Mega Science Project on Indian soil funded by DAE and DST under a Memorandum of Understanding (MoU) with the National Science Foundation (NSF), USA. It is designed to be an “L” shaped detector with 4km arms under ultra high vacuum, with high power continuous laser and highly sophisticated optics. It will be executed by four lead institutions in India (DCSEM, IPR, IUCAA, RRCAT) in collaboration with several institutions and universities in India and abroad. A site in the Hingoli District of Maharashtra has been identified for the project. The unprecedented precision technology that will be used in LIGO-India will enable development of skill sets that hold promises for a giant leap in future science and technology efforts in India.

India has been playing a lead role in Gravitational Wave Astronomy for several decades. More than hundred researchers from India are currently part of the international LIGO-Virgo-KAGRA (LVK) Collaboration. These members, who come from more than a dozen of institutions in India, have been participating in the LVK Collaboration through a single body, LIGO-India Scientific Collaboration (LISC). Many of these members were authors of the papers announcing the first detection of gravitational waves in 2015. LISC members are deeply involved in both theoretical and experimental aspects of GW research and they will be the primary beneficiaries of new GW projects in India.

LIGO-India is proposed to have the same sensitivity (A+) which the other two LIGO detectors plan to attain around the time LIGO-India is scheduled to come online. It is essential for all the detectors in a network to have similar sensitivities to ensure optimal scientific impact. The technology for A+ is nearly finalised. A 10-m prototype interferometer is under installation at RRCAT. The LIGO-India experimental community is likely to play an important role in future upgrades (e.g., LIGO-Voyager) and next-generation ground and space-based detectors.

The project requires development of ultra narrow line-width lasers with high powers, squeezed state lasers, expertise and facility for fabrication, testing and characterisation; ultra-flat optics of $\lambda/3000$; expertise in vibration isolation technology; electronics control techniques; advanced signal recovery techniques; contamination control techniques; Quantum Metrology that uses the quantum mechanical nature of light (and matter) to improve measurements beyond the Standard Quantum Limit (SQL); etc. These highly sophisticated technologies and associated expertise can have immediate use in a wide range of industrial and technological applications in different domains.

The LIGO detectors require an ultra-high vacuum (UHV) system involving about 8 kilometre long tubes with 1.2m diameter, totalling about 10,000 cubic meters of vacuum kept at 10^{-9} torr. This is one of the largest UHV systems in the world. LIGO-India will need to replicate this UHV system. Building this facility is going to be a highly challenging task, not only due to the sheer volume to be kept under high vacuum, but also due to high accuracy levels required to be maintained during manufacture and installation.

In general, it will require major involvement of Indian industries to build the LIGO-India detector, and demands constant collaboration between industry and academia. Experience of such an endeavour promises to take the industrial capabilities of the country forward by a large stride. The project will also create trained manpower who can work on precision instrumentation in highly controlled environments, which will have potential applications in a number of S&T areas, ranging from biotechnology, materials science and laser applications to space labs and other Mega Science Projects with overlapping requirements.

5.2 Other International Mega Projects with Indian Contribution

As mentioned in the previous Section, India is already a partner in three international astronomy mega projects and will make significant contributions to these projects. In addition to these, there are a few other international projects to which some Indian institutions are contributing. While some are through partnerships in observatories, a few others are through participation in the design and/or early development stages.

5.2.1 Vera C Rubin Observatory - Legacy Survey of Space and Time

The Vera C. Rubin Observatory houses the 8.4-meter Simonyi Survey Telescope with the goal of conducting a 10-year Legacy Survey of Space and Time (LSST). The LSST will image the sky continuously each night in six different filters, on an automated cadence, and over the course of the ten-year survey will collect about 800 images of each location in the sky. Located in Chile, it is funded by the National Science Foundation, U.S.A, the Department of Energy, U.S.A and the LSST Corporation (LSSTC). The LSSTC supports science collaborations in pre-survey activities and also builds agreements with international affiliates that contribute to the support of LSST operations.

The LSST is an ambitious project that will take giant strides toward understanding the Universe by mapping out a large part of the observable sky repeatedly. The key science areas that Rubin is expected to address are: (1) cosmology: probing dark energy and dark matter; (2) solar system: making an inventory of objects in the solar system; (3) extragalactic science: evolution of galaxies and their connections to dark matter; (4) transients: monitoring and exploring the transient sky; and (5) mapping the Milky Way via faint stars.

Six different institutes in India (IUCAA, IIA, TIFR, NCRA, IIT-B and IIT-Indore) are working to establish the Rubin-India Consortium to participate in the Rubin project. Each of these institutions will provide an in-kind contribution towards different subsystems within the Rubin project in return for data rights for a specified number of scientists at these institutes. The proposed contributions have been reviewed favourably by the Rubin project and are under consideration by the US funding agencies NSF/SLAC/AURA.

The Rubin-India consortium will collectively have 22 (+ possibly 5 more) PI positions for data access to Rubin, divided amongst the different institutions based on the fraction of their in-kind contributions. Every PI position comes with 4 associated junior PI positions for the entire duration of the Survey and is likely going to benefit about 150 students and 200 postdocs during the entire duration of the Rubin Project.

The different in-kind contributions proposed by the institutions in the Rubin-India consortium concern various Rubin subsystems which deal with the different key science areas of cosmology, extragalactic science and transients, in addition to core contributions to the software infrastructure. In addition, there is considerable interest in all of the scientific areas that can be addressed by Rubin.

5.2.2 Cherenkov Telescope Array

A global effort to construct the next-generation array of imaging atmospheric Cherenkov telescopes (CTA) in both hemispheres of the world is currently underway. The main performance goals of the CTA project are as follows: (i) wide energy range coverage, from few tens of GeV to beyond 300 TeV; (ii) sensitivity of at least one order of magnitude better than any existing Cherenkov telescope installation, viz. achieving 1 milliCrab sensitivity between 100 GeV and few TeV; (iii) improvement in angular resolution and energy resolution to study morphology of galactic γ-ray sources; (iv) having a wide field of view to study extended sources of γ-rays; and (v) having two observatories, one in the south with focus on galactic γ-ray sources and the other in the north with greater focus on extra-galactic sources.

BARC, TIFR and SINP from India have been contributing to CTA since its design phase in 2011 and efforts are on for an Indian participation in the second phase of construction.

5.2.3 Mauna Kea Spectroscopic Explorer

The Mauna Kea Spectroscopic Explorer (MSE) is a planned 11.25-meter aperture segmented telescope dedicated to carry out multi-object spectroscopy, with the ability to simultaneously measure thousands of objects, in three spectral resolution modes: low resolution of R ~ 3,000, moderate resolution of R ~ 6,000 and high resolution of R ~ 40,000. The primary mirror of the MSE telescope has 60 segments in total with each of them measuring 1.45-m in diameter. Together, they give a monolithic shape to the primary mirror.

The Indian participation at present is through IIA, as an associate member of the MSE project. IIA is contributing to design aspects of the primary mirror. The scope of the development of the primary mirror system for MSE includes design and optimization of the Segment Support Assembly to support MSE primary mirror segments, finite element modelling and simulation for the MSE mirror segments, optimisation of the mirror figure for static, dynamic and thermal loads for both zenith and horizon pointing scenarios and development of the primary mirror segments support cells.

5.3 Mega Science Projects in Planning Stages in the Country

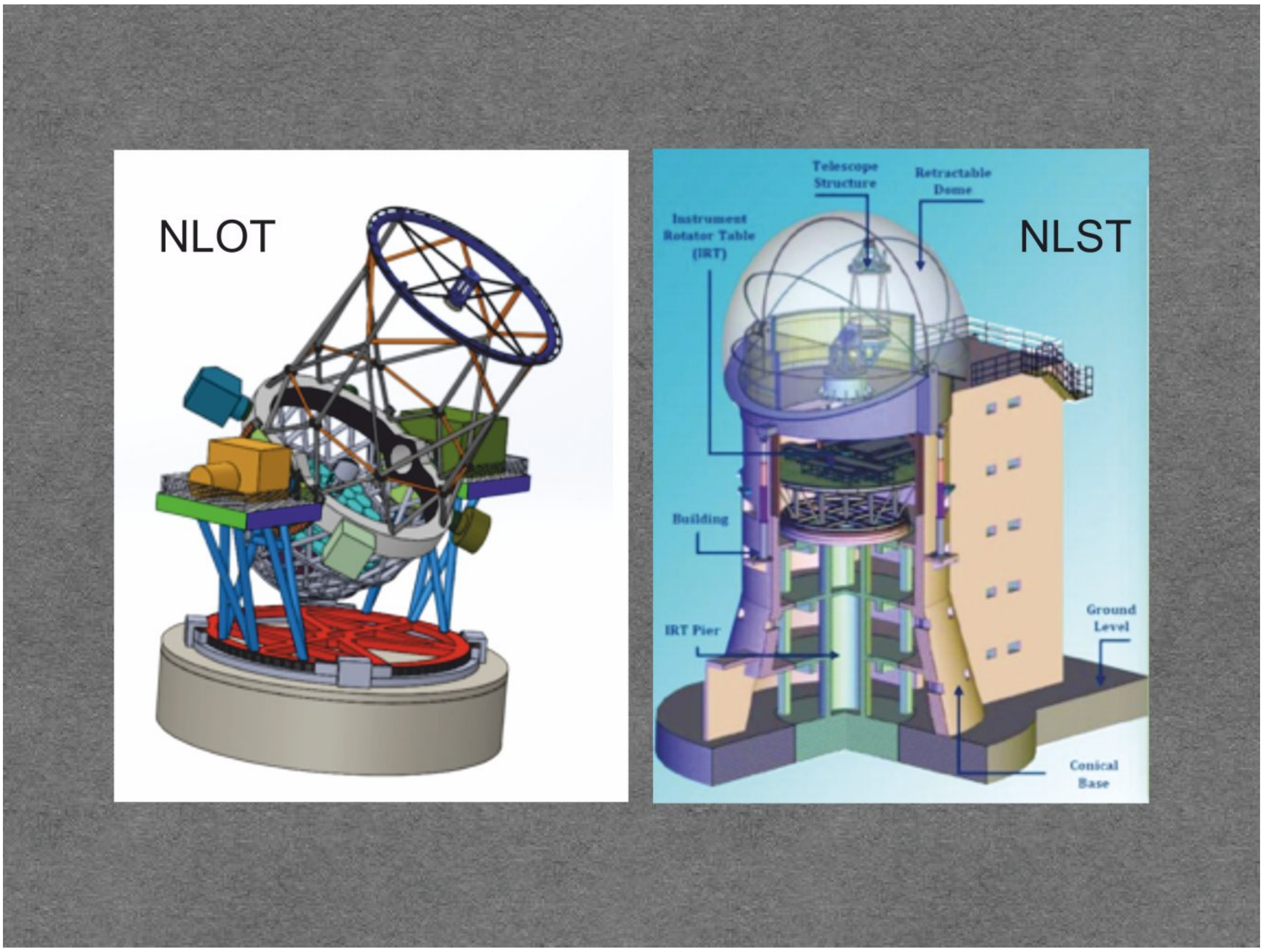

Figure 11: *Artistic impressions of National Large Optical-IR Telescope (left) and National Large Solar Telescope (right).*

5.3.1 National Large Solar Telescope

The Indian solar physics community has envisioned the National Large Solar Telescope, hereafter NLST, as its flagship ground-based facility to observe the Sun at very high resolution. This state-of- the-art facility (comparable to the best in the world) will uniquely position the Indian solar community to tackle several outstanding questions in solar physics and will put India at the forefront of exciting developments is this field. The NLST will be a 2-meter class telescope, whose innovative design, large collecting area, diffraction limited observations and post focus instruments are aimed at revealing the fundamental nature of magnetic fields in the atmosphere of the Sun.

Given that solar observations are possible only during day time from a given location, near-continuous observations for capturing dynamic and transient solar phenomena necessitates placement of solar observatories at different longitudes. This is especially important given the need to constrain the solar sources of space weather phenomena that impact Earth's proximal space. With large observatories either already in existence, or planned, in the United States, Europe and China, a large solar observatory in India fills up a crucial gap in global coordinated studies of the Sun. The proposed location of NLST is identified to be near the Pangong Tso lake in the newly established Union Territory of Ladakh. Here, the observing conditions have been deemed to be ideal.

The proposed design of the NLST is based upon proven technologies that would enable the facility to become operational in less than five years. NLST will be built with international partners providing access to state-of-the-art technologies, while important and substantial components will be developed within India, some with industrial partnerships. The construction of NLST will offer a significant stimulus to India's optical, electronic and technical work force and catalyze future capabilities.

When commissioned, NLST is expected to be a unique research tool for the country and the world. Located on Indian soil, it will attract several talented solar astronomers to the country and provide a superior platform for performing high quality solar research. The construction of NLST, and the envisioned back-end instruments, would demand overcoming several technological challenges and generate several spin-offs both directly and indirectly. The telescope will enable us to continue India's tradition of solar studies established more than a century ago and will be a driving force for innovation in advanced instrumentation for the community.

In addition to the scientific benefits, the telescope project will spur new economic developments in the Ladakh region and offer direct and indirect employment opportunities for the local population. Given its remote but geopolitically significant location, this facility has great socio-political relevance for the region of Ladakh and the Indian Himalayas.

Proposed and led by IIA, the NLST includes participation by several other institutions such as the Udaipur Solar Observatory (PRL), ARIES, ISRO, IISERs and IITs.

5.3.2 National Large Optical-NIR Telescope

A 10-12–meter class telescope in India, the National Large Optical-IR Telescope (NLOT), has been identified as the need of the hour for Indian astronomers. Having a 10-12–meter class telescope in India will provide the optimal facility to pursue multi-messenger astronomy and be competitive with the international community. Internationally, the existing 8-10–meter class telescopes have been set up chiefly in Hawaii or Chile. Other large telescopes exist in N. America, S. Africa and Canary Islands. However, there is no 10-meter class telescope in Asia or Australia. A 10-12–meter class telescope in India, at a good site like Hanle, would fill the 'longitudinal gap', and would be crucial for multi-messenger and time-domain science.

India is partnering to build the 30-meter telescope, the TMT. Access to the TMT will no doubt enable Indian astronomers to do cutting-edge science comparable with their peers elsewhere. *However, the gap between the current largest telescope (3.6-meter DOT) and the 30-meter telescope is huge. A 10-12–meter class telescope in the country is essential to effectively utilise India's share of observing nights with the TMT as target selection for observations with the TMT will come typically from the 10-meter class telescopes. The 10-meter telescope will also be essential to train a large number of students and postdoctoral fellows to generate science cases for the TMT.* There clearly is a requirement for Indian astronomers to have access to a 10-meter class telescope equipped with state-of-the-art instruments. In addition to the benefit for scientific pursuits, a telescope of this class will provide an excellent platform to test new instrument concepts that can help plan future generation science and instruments for the TMT.

The design of the NLOT is based on segmented mirror technology, very similar to that used in the Keck telescopes, and being used in the TMT and the European Large Telescope. Our participation in the TMT project is bringing into the country many of the critical technologies related to segmented mirror telescopes. The M1 mirror systems in TMT, MSE and the NLOT are all of similar dimensions. Hence, the experience gained through the TMT and MSE will be highly beneficial for the realisation of NLOT. Sufficient expertise already exists in the development of instruments for the existing 1-4-meter class telescopes. Additionally, we are gaining good experience in the design and build of backend instruments for large telescopes through our participation in the TMT project. All of these can be translated to building a 10-meter class segmented telescope with state-of-the-art, advanced-technology backend instruments within the country. Several industries in India are currently partnering with scientific institutions towards participation in the TMT, SKA and LIGO projects and these would be partners in the development of the NLOT.

The build of a 10-meter class telescope within the country will not just enable effective use of the technical know-how gained by the R&D institutes and industry through our participation in the TMT, but also the development of additional state-of-the-art high-end technology in areas such as optics, civil, mechanical, electronics and software engineering. The presence of an Indian 10-meter class telescope would encourage and attract young talent within the country and help in further growth of the Indian astronomical community. More importantly, as a collateral benefit, the execution of such a large, technologically advanced project will benefit all of STEM.

A national effort, the NLOT project is led by IIA with active participation from other institutions such as TIFR, IUCAA, ARIES, IITs, IISERs and universities that are involved in research in astronomy and astrophysics. Working towards the development of a detailed project report, efforts are on at IIA towards the generation of detailed science requirements, design and verification of the telescope optics design, concept design of the telescope structure and dome, and generation of requirements for instruments.

5.3.3 Network of Telescopes and Dedicated Survey Facilities

Worldwide, small telescopes (i.e typically 1-2-meter class telescopes) are increasingly being dedicated to undertake systematic surveys. These are either standalone facilities (such as the SDSS, PanSTARRS, ZTF, etc.), or a network of telescopes spread across the globe (such as ASAS-SN, MASTER, BOOTES etc.). In particular, such facilities have been very successful in carrying out wide field imaging surveys. Equipped with automated, pipeline data analysis software, these surveys are very efficient in rapid dissemination of discovery of new transients that enables quick follow-up studies. Additionally, such facilities are also set up for limited science use, such as for rapid response follow-up studies of new transients, survey of Near Earth Objects (NEOs) and space debris.

With the increasing number of modern technology facilities globally, to remain competitive, it will be useful to explore the possibility of undertaking specific surveys using our existing facilities. Such dedicated surveys may need some very specific instrumentation and/or modifications to the existing telescopes. It is also important to design these surveys keeping in mind the various ongoing and/or proposed surveys by the international community (e.g. Gaia, Kepler, TESS). A well-planned survey will provide interesting targets for large facilities like TMT and SKA for detailed follow-up studies.

At present, the country lacks wide field optical telescopes. Telescopes of this kind are essential for surveys and multi-messenger astronomy. A network of wide field robotic telescopes across the country (providing photometric and spectroscopic capabilities), taking advantage of the longitudinal location, will be highly beneficial in a quick search for electromagnetic counterparts of gravitational wave sources in the era of LIGO-India, and in the tracking and orbit determination of NEOs and space debris. Small robotic telescopes are also ideal for hands-on remote observing sessions by graduate and undergraduate students.

5.3.4 Future Radio Astronomy

In radio astronomy, at the national level, there are active plans for an expansion of the GMRT facility, as a natural follow-up of what the recent upgrade has achieved. This initiative to expand the GMRT is currently evaluating options which would allow (a) an increase in the resolution (and hence the confusion limit) of the current GMRT, (b) better imaging capabilities for diffuse, extended structures, and (c) increasing the instantaneous field of view of the antennas. Detailed design studies and trade-off analyses are underway for these different options, alongwith early prototyping of some of the crucial technologies. The expanded GMRT (eGMRT), when realised, would significantly enhance the low frequency radio astronomy capabilities in the country, keeping it relevant in the era of SKA Phase-1.

Depending on the timeline of completion and success of the SKA Phase-1, plans for an expansion to the Phase-2 will be initiated, likely in the early 2030s. In keeping with this, the SKA project will continue to invest in R&D for these future needs, even as the Phase-1 is being constructed. Plans for India's participation in the SKA also envisage support for R&D activities during the construction phase of SKA, for investing in future technologies for both in-country facilities (such as the eGMRT) and for continued meaningful participation in later phases of the SKA project.

5.3.5 Himalayan Sub-Millimeter Facility

The sub-millimeter (sub-mm) sky is a unique window for probing the architecture of the Universe and structures within it. From the discovery of dusty sub-mm galaxies to the ringed nature of proto-stellar disks, our understanding of the formation, destruction, and evolution of objects in the Universe requires a comprehensive view of the sub-mm sky. In the past two decades the mm/sub-mm interferometers have enabled views into the finer details of regions/objects at the highest resolutions ever achieved leading to fantastic discoveries including the first image of a supermassive black hole at the center of an external galaxy. In spite of the importance of sub-mm wavelengths, there is at present no telescope facility in India to observe and study at these wavelengths.

Although sub-mm observations are possible from ground-based facilities, the observations are constrained to several “windows” due to the atmospheric water vapor content. Lower the water vapor content, lesser the fraction of light that is absorbed by the atmosphere at sub-mm wavelengths. This becomes increasingly crucial at shorter wavelengths, where observations are only possible when the water vapor content is lower than a certain threshold. Hence, sub-mm facilities worldwide are located at high-altitude dry places.

The Himalayan high-altitude desert region of Ladakh has numerous potential high-altitude sites at 5000–6000m amsl accessible by partly paved roads. Such sites could provide access to sub-mm/THz wavelength bands for astronomical observations. IIA recognized the importance of the Himalayas and pioneered the development of astronomy sites in the high altitude deserts of the Himalayas, specifically, at Hanle, Ladakh. Site testing shows that the precipitable water vapor content of Hanle is similar to that of Mauna Kea. Establishing a sub-mm/THz facility thus needs exploration and development of higher and better sites in the general area which IIA has developed. Ladakh undoubtedly hosts a number of such sites, one prospective site being at the 5000m amsl Pologongka La mountain pass.

The development of a high quality northern sub-mm/THz site and a 15-meter class telescope operating between 200-1100 GHz at a high altitude desert site will allow India to leapfrog to the forefront of research at these wavelengths. Such a site, in combination with technology and community development efforts, will also allow India to leverage international collaborations on an equal footing. Efforts in this direction have already begun, with the Space Applications Center (SAC) of ISRO currently in the process of establishing a 6-meter facility at Hanle, operating up to 350 GHz (850 μm wavelength). Identification, characterization, development of a site and the parallel development of a 15-meter class antenna and associated instruments will be a mega science project that will propel India and Indian astronomers to doing the cutting edge science in sub-mm wave astronomy and the emerging field of THz astronomy. The location of a 15-meter antenna operating in the Tera-Hertz frequencies in India will bridge the longitudinal gap in the global network of telescopes which operate synchronously to synthesise the earth sized telescope called the Event Horizon Telescope (EHT), through the Very Long Baseline Interferometry (VLBI) technique. The EHT recently imaged, for the first time, the signatures of a supermassive black hole at the center of the M87 galaxy, captivating the entire world. A facility in India, such as the one proposed to be located in Ladakh, will improve the resolution of the images obtained with the EHT, providing greater details of supermassive black holes.

The science drivers for a 15-meter sub-millimeter facility include: questions pertaining to the process and efficiency of star-formation, and the impact of the galactic environment as well as turbulence in the Local Universe; discovery of actively star forming galaxies visible only in the sub-mm; 3-D clustering of star-forming galaxies to understand structure formation; probing the underlying dark matter density fluctuations and the Sunyayev-Zeldovich effect in the distant Universe; and sub-mm study of exotic phenomena such as variable protostars, GRB afterglows and counterparts of fast radio bursts in the Transient Universe.

This proposal is a collaborative work of members of the Indian Sub- mm-wave Astronomy Alliance (ISAA), that brings together scientists from TIFR, IIST, RRI, IIT-Indore, IISc, NISER and IIA.

5.3.6 Ground Based γ-ray Astronomy

The journey of γ-ray astronomy in India using ground-based Cherenkov telescopes over the last two decades has experienced an era of very encouraging and impressive advances at both scientific and technological fronts. To enable more effective and significant contributions in this vibrant, emerging field of gamma-ray astronomy, the future design and development plans are as outlined below:

- Major upgrade of the existing TACTIC telescope at Mount Abu.
- Development of Silicon Photomultipliers (SiPMs) based 256-pixels imaging camera. After successful

completion of tests, installation of SiPM-based telescope at Hanle is planned for dedicated monitoring of known blazars. Subsequently, HAGAR will be phased out in a timely manner as the implementation of SiPM-based telescope progresses.

- Design and development of small-size Schwarzschild-Couder telescopes for TeV gamma-ray observations.
- Installation of a second MACE telescope (MACE-II) at Hanle for stereoscopic observations with the MACE telescope.
- Participation in the multi-messenger observations world-wide and joining the CTA consortium.

5.4 Timeline of the Projects

This section provides details of the status and timeline of the projects described above. Table 2 provides details of the international projects, and Table 3 provides details of the national projects. The projects and facilities listed are observatory class. This means, these facilities, once established will function for a few decades. Facilities of such kind will require funds beyond the construction phase for (a) operations, (b) maintenance and (c) upgrades. All projects have projected periodic upgradation of capabilities to keep up with the rapidly evolving technologies and requirements from the users. Therefore, one can easily envisage an expenditure of 15-20% of the project amount per year beyond the construction phase, for participation during the operations phase. This needs to be factored in the funding scheme of mega projects.

Table 2: *Timeline of the international mega projects*

Project (Internat-ional Mega Projects)	Timeline								Remarks
	Concept	DPR Preparation/ Submission	Initial Development - Design/ Prototype	Approval/ Joining	Level of Partici-pation	Construction	First Light	Operations	
TMT	2009	2010	2012-	Observer: 2010; Partner: 2014	10%	2023-2033	2034	At least 25 years	The Project is delayed from its original projection of 2014-2023 due to site-related issues in Hawaii.
SKA-Phase-1	2009	2014 / 2019 / 2020	2014-2019 2018-2020	In principle approval: 2014; Project Approval: 2023	6-7%	2021-2027	2028 (full array)	At least 25 years	Participation in SKA-Phase-1 approved.
LIGO-India	2010	2019	2019-2020	In principle approval: 2014; Project Approval: 2023	100%	2023-2030	2031 (First science run)	~15 years	Located and built in India with technical and in-kind support from LIGO-USA.
CTA	2012	2020-2023	2014-2020	Proposal to be submitted	5-10%	2022-2025 (Phase-I) 2025-2030 (Phase-II)	2031	~15 years	Propose participation during Phase-II.
MSE	2017	2025	2017-2028	Associate Member (IIA): 2019 Proposal for construction phase to be submitted	10% (in kind)	2028-2038	2038	~20 years	Proposed 10% participation is through production of 50% of the primary mirror segments

Table 3: *Timeline of the national mega projects*

Project (National)	Timeline								Remarks
	Concept	DPR Preparation/ Submission	Initial Development - Design/ Prototype	Approval/ Joining	Partici-pation Level	Construction	First Light	Operations	
NLST	2007	2012-2017	2010 (Telescope Concept design) 2017-2023 (Dome and instruments design)	Funded for land acquisition in 2019	100%	2022-2028	2028	At least 25 years	DPR submission in 2017. Land acquired at Merak, Ladakh in 2019. Awaiting approval and funding for construction.
NLOT	2008	2019 / 2020 - 2024	2017-2022 (Prototype Segmented Mirror Telescope, Telescope and Dome design) 2020-2025	Proposal for initial funding submitted in 2019.	100%	2025-2035	2036	At least 25 years	Proposal submitted in 2019 for initial funding for design and prototype development and preparation of DPR. Awaiting approval.
Sub-mm/ Terahertz	2020	2022 - 2024	Proposal to be submitted	Proposal to be submitted	100%	2025-2030	2030	At least 20 years	Significant experience will be gained by the 6m telescope development (2020-2023) by ISRO-SAC that will be located at IAO, Hanle.
Ground-based γ-ray (MACE-II & SCT Array)	2018	2022	2022	2022	100%	MACE-II: 2025-2030 SCTA: 2030- 2035	2030-2035	At least 10 years	Technology based on already established facilities.

It is emphasised here that the projects listed in the Tables 2 & 3, together with the proposed space missions, will provide multi-messenger, multi-wavelength windows to the Universe.

5.5 Priority of Projects

It is recommended that further commitments in the already committed mega projects (such as TMT, SKA and LIGO) be honoured and mechanisms be evolved to maximize scientific, technical and other types of value returns. In addition, priority may be given to indigenous facilities that use technological know-how learnt from participating in the international mega projects (such as mentioned here). Such facilities are also absolutely essential for our community to grow quickly so that we will be able make efficient use of, and build large instruments for, facilities like TMT, SKA and LIGO-India. Priority is also to be given to indigenous facilities that will place Indian astronomy at par with the international community and/or open new windows that currently do not exist. Emphasis is to be placed on development of prototype instruments with new technologies that can eventually lead to development of instruments for the international mega facilities. There needs to be a focus on building an integrated data archive and distribution facility for all astronomy resources in the country. Based on these considerations and the present needs of the Indian astronomy community, a priority list of the projects is provided. Astronomy being a multi-messenger and multi-wavelength science, it is important to have facilities for broad spectrum observations. The projects are hence prioritised under various categories as listed in Tables 4 & 5.

Table 4: *Category-Wise Priority List of Mega Projects.*

Project	Status	2020-2025	2025-2030	2030-2035
OPTICAL & IR				
1. TMT	International (8-10%)	Development & Construction	Construction	Completion of construction; First Light & Commissioning
2. NLOT	National	Detailed Design Development & DPR	Pre-Construction Development; Construction	Construction
3. Mauna Kea Spectroscopic Explorer	International (~ 10%)	Design Development	Pre-Construction Development	Pre-construction Development; Construction (2033-2038)
SOLAR				
1. NLST	National	Project Approval & Construction	Construction & First Light	Commissioning & Early Science
RADIO				
1. SKA Phase-1	International (6-7%)	Development & Construction	Construction & First Light	Commissioning & Early Science
2. SKA Phase-2	International	-	-	Early Construction
GRAVITATIONAL WAVE				
1. LIGO - India	International	Development & Construction	Construction, First Light & Commissioning	Early Science Operations - First science run in 2031

Project	Status	2020-2025	2025-2030	2030-2035
SUB-MM / TERA-HERTZ				
1. 15m Sub-mm Antenna (HSMF)	National	Design & Development	Construction	Early Science Operations
ɤ-RAY				
1. Second Generation Facilities (MACE-II & SCT Array)	National	Development & Build	Installation of MACE-II	Installation of SCT Array
2. CTA - Phase II	International	Development & DPR	Construction	First Light & Commissioning

Table 5: *Category-Wise Priority List of Projects Required for Development of an Ecosystem for Sustained and Effective Use of the Mega Science Facilities.*

Project	Status	2020-2025	2025-2030	2030-2035
OPTICAL & IR				
1. Participation in international 8-10 m class observatories	International	Use of Telescope	Use of Telescope	Use of Telescope
2. Network of small telescopes	National	Project Development	Construction	First Light & Commissioning
3. NLOT - Second Generation Instruments	National	-	Development of Science Cases & Requirements	Concept Design
RADIO				
1. eGMRT	National	Design Development	Construction	Commissioning & First Light

Project	Status	2020-2025	2025-2030	2030-2035
SOLAR				
1. NLST - Second Generation Instruments	National	Development of Science Requirements	Design Development	Build of Instruments
CAPACITY BUILDING				
Technology & Human Resource Development	National	Feasibility studies, development of new technologies, skill development (including through training programmes at undergraduate and graduate levels)		
COMPUTATIONAL REQUIREMENTS				
High Performance Computers	National	Configuration, procurement, installation and use		

It is noted that most mega projects will require an initial seed money during a pre-project phase for several activities such as (a) exploration and establishment of the nature of Indian contribution in the case of international projects, (b) requirements and design development, (c) prototype development and technology capacity building, (d) development of project partnership and workshare agreements, etc. The quantum of the initial funding would be dependent on the project and its requirements.

It is to be borne in mind that there would be other projects which may be proposed in the future. The absence of any such project in this document should not preclude their consideration, especially if the projects are bringing in new dimensions in terms of the science that can be done and/or in terms of unique technologies that they may provide exposure to. Support for large international collaborations that may emerge through science generated by the use of the mega science facilities is highly desirable.

5.6 Space-based Astronomy Missions

World-wide, in the next decade, space astronomy will be dominated by the multi-mirror James Webb Space Telescope (JWST), followed by the Nancy Grace Roman Space Telescope (NASA mission planned for 2025) and EUCLID missions, all operating in the infrared region. A few X-ray missions are also proposed. However, there are no planned missions in the UV range. The success of the AstroSat has paved the way for the development of astronomy satellites in the country. Several missions are proposed for observations in the ultraviolet and X-ray regions. These missions have been proposed under the ISRO's Vision for Planetary Sciences and Astronomy and are being included in this document for the sake of completeness.

5.6.1 ExoWorlds

The last decade has seen the Indian Space Research Organisation (ISRO) make major inroads in the field of planetary explorations. Envisaging a giant leap forward, a pioneering ISRO mission, ExoWorlds, is proposed which holds the promise to be the world-leading facility in the next decade for studies of planets beyond the Solar System – the exoplanets. A few thousand planets have now been discovered displaying extreme diversities in their macroscopic properties. The central goal of this mission is to conduct, for the first time, a comprehensive survey of chemical composition and atmospheric processes of a large population of exoplanets. This would lead to a paradigm shift in our understanding and classification of planetary systems and shed crucial light on their formation and evolution. This breakthrough science goal will be realized through high-precision transit spectroscopy which offers a unique opportunity to probe the exoplanetary atmospheres without the need for direct imaging. To achieve this, ExoWorlds is proposed as a dedicated mission for exoplanet spectroscopy housing a focused payload that comprises a 2-meter class telescope with two medium resolution ($R \sim 500$) spectrometers that will span the entire NUV-Visible-IR spectral range between 0.25 - 5 μm with very high photometric precision. A fine guidance sensor (FGS) along with a fast steering mirror will ensure precise pointing and stability in an L2 orbit. The unprecedented broad and simultaneous spectral coverage with high precision will enable the detection of a rich variety of chemical species; retrieve the pressure-temperature profiles; probe the outer atmospheres for clouds and hazes; and delve into the realms of habitable planets and biomarkers. With a proposed mission timeline of 5 years, ExoWorlds would place the Indian astronomy community at the forefront of the emerging field of exoplanetary science.

Led by the Indian Institute of Space Science and Technology (IIST), ExoWorlds is a collaborative project of IIST, ISRO, IoA-University of Cambridge, TIFR, IUCAA, IIA, PRL, ARIES, SNBNCBS, IISER-Kolkata, Christ University-Bengaluru and St. Joseph's University-Bengaluru.

5.6.2 Indian Spectroscopic and Imaging Space Telescope (INSIST)

To complement the missions in the IR wavelength range, a deep imaging instrument in the UV range is proposed. The Indian Spectroscopic and Imaging Space Telescope (INSIST) will produce high-resolution deep UV-optical images, and will also have capabilities to carry out low to medium resolution spectroscopy. The INSIST mission is a collaborative project between various institutions in the country, such as IIA, IUCAA, ARIES, PRL, TIFR and Christ University with IIA as the lead institution. Collaboration with the Canadian Space Agency that is developing a very similar mission is also being explored.

The INSIST mission will explore a variety of galactic and extragalactic sources, including SNe, GRBs, globular clusters, young massive clusters in nearby galaxies, star-formation in regular spiral galaxies as well as various dwarf systems both in the local and distant Universe. Going beyond the scale of galaxies, INSIST, as part of its survey programmes, will also explore clusters, filaments and voids in the UV/optical wavelength.

The INSIST proposal was recommended by ISRO for pre-project phase with seed funding in March 2019. Two years of the pre-project phase resulted in a detailed science document with necessary simulations, design documents and initial tests of some critical components. The project is expected to move to the next phase soon.

5.6.3 Infrared Spectroscopic Imaging Survey

The Department of Astronomy and Astrophysics of TIFR has proposed a small satellite payload, Infrared Spectroscopic Imaging Survey (IRSIS) for Near Infrared (NIR) observations. The scientific aim of IRSIS is to spectroscopically image a good fraction of the sky, which continues to remain unexplored till date in the mid-IR wavelengths (1.7-6.4 micron). This payload would be a fibre bundle based Integral Field Unit (IFU) spectrograph with seamless coverage of the interesting waveband deploying two similar channels for NIR bands of 1.7 to 3.4 micron wavelength and 3.2 to 6.4 micron wavelength.

5.6.4 Daksha - an All Sky X-ray Payload

This is a proposed broadband, all-sky, high-energy transients mission, with the primary objectives of studying the electromagnetic counterparts of gravitational wave events and classical gamma-ray bursts. To achieve these goals, Daksha will use two low-Earth orbit satellites with three types of detectors each. Daksha will have an all-sky coverage, broadband spectral response from 1 keV to > 1 MeV, and will be an order of magnitude more sensitive than the existing missions. All current missions together have, so far, discovered only one electromagnetic counterpart of gravitational wave sources. In contrast, Daksha is expected to detect dozens of such events. Daksha will also have high sensitivity for hard X-ray polarisation, yielding unmatched insights into the central engines of gamma-ray bursts.

Daksha has been recommended as one of the leading space astronomy missions to be taken up for further study for realisation in a few years' time. Seed funding has been provided by the ISRO Space Science Programme Office for developing a laboratory model.

5.6.5 X-ray Polarisation

X-ray polarisation is a vastly unexplored area of X-ray astronomy. A medium energy X-ray polarisation mission, the XPoSat, developed by RRI in collaboration with ISRO centres has recently been launched. The second such mission globally, XPoSat will study X-ray polarisation in selected cosmic sources. A follow-up, comprehensive broad band polarimetry mission is planned by the U. R. Rao Satellite Centre (URSC) and PRL.

5.6.6 Radio Astronomy in Space-based Missions

The international radio astronomy community is working on space VLBI missions, as well as observations from the far side of the Moon, particularly in the low radio frequency regions. The lunar farside provides an ideal location for sensitive measurements, as it is expected to be devoid of terrestrial radio frequency interference (RFI). The lunar farside is especially attractive for experiments seeking to detect the weak cosmological signals from the Cosmic Dawn and the Epoch of Reionization (CD and EoR), when the first sources formed and subsequently ionised the baryonic matter in the Universe. Using the redshifted hyperfine transition of neutral hydrogen as a tracer of these poorly understood cosmological epochs is one of the key science goals of the SKA (Probing the Cosmic Dawn). A measurement of the radio sky spectrum over 40 - 200 MHz with radiometers and interferometers in the lunar farside is expected to provide a clean data set that can bolster confidence in foreground subtraction and systematics control of ground-based counterparts. Furthermore, dedicated experiments for detecting the signals from CD and EoR in the lunar farside are certain to yield groundbreaking results, solving the mysteries of what the first sources of radiation in the Universe were, when they formed, and how they ionised the Universe.

With renewed interest in lunar exploration, these efforts of measuring the metre wavelength radio sky from the Moon are being looked upon favorably by space agencies all over the world. One experiment of note is the Netherlands-China Low Frequency Explorer (NCLE), that made measurements of the radio sky, in orbit around the Moon, in late 2019. NCLE operated over the 80 kHz - 80 MHz range. Several more experiments are expected to follow from countries around the world, in the form of lunar orbiters as well as interferometers deployed on the far side lunar surface. Of particular interest are the LuSEE, ROLSES and FARSIDE experiments from the United States, which are selected radio astronomy experiments that will operate on the Moon or in lunar orbit.

In India, PRATUSH – Probing ReionizATion of the Universe using Signal from Hydrogen – is an experiment that has been proposed by researchers at the RRI. PRATUSH will be a custom designed, precision spectral-radiometer operating over 10-250 MHz, in orbit around the Moon. With a dedicated science goal of detecting the global (sky-averaged) signal from CD and EOR, it will make scientific measurements from the lunar far side and transmit data back to Earth when in the near side, thereby overcoming the limitations faced by ground based experiments on the Earth. With decades of experience in building ground-based precision radiometers, the group at RRI is now looking towards taking this expertise to the lunar farside. PRATUSH is currently in pre-project studies mode under an announcement of opportunity for astronomy payloads by ISRO (announced in 2018).

The space-based radio astronomy era is blossoming. With concerted effort to explore these unchartered territories for scientific measurements, India can be at the forefront of the international radio-astronomy space-race in the modern era.

5.6.7 Space-Based Solar Missions

The inter-disciplinary domains of solar astronomy, space weather and space sciences, collectively referred to as heliophysics, address the intersection of fundamental solar physics and translational research to characterize space weather and its impact on planets and our space-based technologies. Following the launch of India's first solar space mission Aditya-L1, the Indian heliophysics community has deliberated and converged upon a vision for solar and space weather observations from space that will complement and add to our (proposed) ground-based capabilities. Successful implementation of this vision over the course of next 15 years will place India at the forefront of space science and will enable India to generate indigenous data for observation, assessment and forecasting of the space environment.

A Pioneering Space Weather Mission to Lagrange Point L5: With significant investments in space assets, it is critical for the Nation to become self-reliant in generating space weather information to protect its space-based and space-reliant technologies. In this context, the community has envisioned a mission to the stable Lagrange point L5 which provides opportunities to continually monitor the Sun-Earth system and return actionable space weather information. A specific advantage of this location is advance observations of the solar disk that rotates to the Sun-Earth line in 4-5 days. These advanced observations allow assessment of solar active regions (magnetic field concentrations) that may generate solar storms. This location also samples, a few days in advance, the in-situ space plasma environment (co-rotating interaction regions) that the Earth encounters. The L5 location is also a unique vantage point for observing the Sun-Earth line continuously. This allows constraining the dynamics of Earth-directed magnetic storms such as CMEs with high accuracy, which in turn aids accurate CME arrival time forecasts. Overall, the L5 vantage point is considered the most ideal location for a space weather observatory. Ideal instruments for a space weather mission to L5 would include: i) a Vector Magnetograph and Helioseismic Imager for assessing the potential of solar active regions and measuring solar internal plasma flows, ii) Heliospheric Imager for observing CMEs along the Sun-Earth line, and iii) in-situ plasma diagnostics instruments (magnetic fields and charged particle flux) for assessing space environmental conditions.

The Indian solar physics community has already put in concerted effort and thoughts into a plausible L5 mission and other space agencies such as NASA and ESA are beginning to consider this possibility as well. *If implemented within the next 5 years, India has a chance to be the first country to have a comprehensive space weather observatory located at this uniquely advantageous location in space.*

A High Resolution Solar Observatory in Low-Earth Orbit: To complement ground-based high resolution observations, a space-based high resolution solar observatory is necessary as it allows near-continuous observations of the Sun (without being impacted by the day-night cycle on Earth) that are not impacted by atmospheric seeing conditions. Understanding small-scale magnetic reconnection and wave mediated coronal heating, the genesis of solar flares and CMEs in localised magnetic field concentrations and the flow of energy from the solar surface to the atmosphere requires high resolution, high temporal cadence observations of solar magnetic fields and plasma. This would require simultaneous, multi-line spectro-polarimetry to cover different atmospheric layers; line-resolved EUV and X-ray polarimetry; and multi-wavelength, high resolution imaging capabilities.

Given the massive data that such a mission would generate and telemetry requirements, such a mission would ideally be located in Low-Earth Orbit (LEO). Successfully implementing this mission would require the development of novel instruments that would further advance national research and development ecosystem.

5.7 Large Computing Facilities and Databases

The increasing volumes of large format, high resolution (spatial and spectral) data with high sensitivity are providing information about the Universe at scales not witnessed before. This is expected to increase in the future with data from various large projects. Such data are challenging our present ability to analyse the data, and also our theoretical understanding, requiring better simulations. Also, it is important to make the large volumes of data accessible to larger communities through databases. These require efficient and high performance computing facilities, large data servers and implementation of machine learning and artificial intelligence techniques. Discussed below are some specific areas and facilities that have special computing needs.

5.7.1 Computational Centre for Space Weather Forecasting

Space-based observations of solar activity (through remote imaging instruments) and (in-situ) measurements of local variations in space provide important constraints for space weather phenomena. These observations, however, do not generate the comprehensive information that results in a holistic understanding of cause and effect, i.e., origin-to-impacts. An observation is made when a space weather event (say, flare) has just occurred or is occurring, or an interplanetary disturbance (such as a CME) is already near-Earth. This does not provide the necessary time window for space weather forecasts that can be translated to mitigation strategies by national space agencies, defense establishments and space-reliant industries. Thus, space- and ground-based observations need to be supplemented by data-driven computational magnetohydrodynamic models (i.e., physics based simulations) and Artificial Intelligence and Machine Learning algorithms to return actionable space weather forecasts. This is already realized by advanced space-faring nations, with the US having established the NOAA Space Weather Prediction Center, UK Met Office hosting the UK SpaceWeather Unit, the European Space Agency hosting the Office of Space Weather and China establishing the State Key Laboratory for Space Weather.

Indian expertise in the domain of computational space weather forecasting, while still limited, is growing with the multi-institutional Center of Excellence in Space Sciences India at IISER-Kolkata taking the first initiatives to develop predictive space weather models. The solar, space sciences and heliophysics communities recommend rapid escalation of these efforts towards creation of a national space weather modelling and forecasting center, which relying upon multi-institutional expertise, can generate indigenous space weather forecasting capabilities for India. This translational activity will immensely benefit multiple sectors such as space, defense, communications and civil aviation.

5.7.2 For Radio Astronomy – SKA

The SKA telescope, when it becomes operational, will produce several hundred petabytes of scientific data every year. This prodigious volume of data will require a complete paradigm shift in the working model of radio astronomers. They will no longer be able to download data to their desktop for analysis and interpretation. SKA data analysis will require the incorporation of what is presently considered specialized, rare and centralised High-Performance Computing (HPC) and data analytics systems into the very fabric of operational facilities. Alongside this, considerable innovation will be needed in algorithms and methodologies for the analysis of these huge datasets. Advanced tools will need to be developed to enable visualisation of large data volumes as well as for finding rare astronomical objects whose discovery may be paradigm-changing. India is uniquely positioned to leverage its well-developed software skills and its aspirations in high-performance computing to fulfil this critical role.

The resources needed to fully process, distribute, curate and utilise data flowing from the SKA observatory represents an enormous challenge. To develop a plan for an international network of data centres - referred to as SKA Regional Centres (SRCs) - the SKA organisation (SKAO) has formed the SRC Coordination Group with active Indian participation.

The SRCs are required to provide the compute, storage and analysis/visualisation capabilities needed to handle exabyte-sized datasets. It is expected that there will be several such SRCs located across the globe. The SKAO and the network of SRCs will need to work collaboratively to shape and establish a shared, distributed data, computing and networking capability that draws on international cooperation and supports the broad spectrum of SKA science. The full SRC network is expected to be operational by 2029, with one node planned to be located in India. Over the multi-decade operation of the SKA, the SRCs will provide the computing resources needed by the international community for maximal scientific utilisation of SKA data. A small scale prototype version of the SRC that can cater to the needs of the SKA precursor and pathfinder facilities, such as the upgraded GMRT, will be made operational by 2024, and the full-scale SKA Phase-1 compatible version is planned to be ready by 2028, with periodic technology refresh activities planned every subsequent 4-5 years.

5.7.3 Gravitational Wave Astronomy - Data Analysis and Numerical Relativity

Detection of gravitational waves in noisy data requires enormous amount of computing power. Several searches for GW are presently limited by computing power. For example, the searches assume the spins of the binary components are aligned with the orbital angular momentum, without any strong physical motivation. Thus, at present, the chances of detection of binaries with non-aligned spins are less. The computation power necessary to relax this assumption in the models is orders of magnitude more than currently available. A hybrid scheme to "interpolate" numerical relativity templates in the parameter space is used even for the present simpler searches. While several algorithms are being developed to speed up computation, state-of-the-art data centres are being built for such analyses across the world by the international community. IUCAA has built a data centre with ~ 500 TeraFlops peak theoretical computing power, which is expected to ramp up by the time LIGO-India comes online.

5.7.4 Requirements of Other Mega Projects

As with SKA and LIGO-India, other mega projects such as TMT, NLST, NLOT, etc. require significant amount of computational resources for project specific requirements. These requirements include data acquisition, preliminary analysis, data centre for storing raw data and computational platforms for analysis of data. Some of the instruments, such as integral field units and fibre based spectrographs, generate large data volumes during each observation that require special platforms for analysis. The data are often processed in batches, and with the recent progress in machine learning and related techniques, it has become possible to explore data for unanticipated features as well. Each mega project also requires resources for making data available: raw data as well as data products and catalogs need to be made available to all users to ensure optimal utilisation of the data.

5.7.5 Virtual Observatories

Virtual Observatories (VOs) are repositories of archival data equipped with not only the option of downloading data but also for analysing data. This builds on the convention in astronomy that all data collected by large facilities are made public after a certain lock-in period to ensure maximum possible usage of data. This has become particularly important in the era of multi-wavelength and multi-messenger astronomy where data from very diverse sources is used together to derive inferences about properties of sources. The capability of analysing data prior to download is essential as some of the raw data products are too large to be downloaded or processed on small facilities. Therefore, in the next two decades, we need to support addition of high end computing along with VO servers to optimise the usage of data archives. Similar support is also required for other dedicated data archives like AstroSat, GMRT, Aditya-L1 and ground-based optical telescopes. As one is envisaging a very large data base, it is desirable to implement various advanced techniques like Artificial Intelligence and Machine Learning for search and analysis of the data.

5.7.6 Common Facilities for Computational Astrophysics

Computational Astrophysics comprises a variety of applications, from N-Body simulations, hydrodynamic simulations, MHD simulations to detailed analysis of large data sets using statistical techniques as well as modern approaches like Machine Learning. Considerable computational work is also required to check feasibility of planned experiments and facilities and to fine-tune their capabilities to ensure that it will be possible to discriminate between competing scenarios. At present, we have expertise in these areas spread across a large number of institutes and universities. Each institute and university, depending on resources available, provides computing facilities for such work. However, we do not have any functioning equivalent of the national science supercomputing center in the US that provides facilities and support to all researchers in the country. Such facilities provide some amount of computing time and resources free of cost to enable researchers to test and demonstrate capabilities of their codes. Researchers who require more resources need to pay for the same through research grants, or submit proposals for fully-funded computer time. It is worthwhile exploring the provision of a common supercomputing facility for the astronomy community, to be upgraded from time to time.

In principle, the National Supercomputing Mission (NSM) can provide some of the resources required here. However, in practice, the access to NSM facilities for users beyond the host institute needs to be streamlined with adequate help for customization to the local development environment.

It is important to note here that the astrophysics community in India has been making use of machine learning and related techniques for data analysis for several decades. The community has been a leader in terms of code development for research. Therefore, any investment in facilities is likely to result in significant returns in terms of research as well as human resource development.

The astronomy community can also explore the use of cloud computing and data storage on the cloud as a potential platform for HPC. This can potentially free up the overheads for purchase and maintenance of hardware and the need to continuously upgrade systems.

6 FUNDING, MANAGEMENT AND EVALUATION OF PROJECTS

All Mega Science Projects (MSPs) are generally multi-institutional / multi-organisational with pan-India participation. They are typically long-term and require significant resources. A successful project also requires an effective and efficient management, fund management and evaluation structure. While these aspects are already in place to a large extent, it is important to have, by and large, a common structure for all MSPs that ensures sufficient transparency, accountability and efficiency in the process of funding and monitoring.

6.1 Proposal Phase

Proposal development: MSPs require the participation of scientists and engineers from multiple organisations with varied expertise to collaborate and work towards a common goal. To achieve this, it is important to engage in a community planning exercise right from the proposal development phase through discussions at national level meetings, formation of working groups, etc. Such exercises will enable identification of the key science goals, facility requirements to achieve the same, and also evaluate the scientific expertise and other skill-sets available within the country for a successful implementation of the MSP.

Submission of proposals: The funding for MSPs could come from multiple agencies leading to an ambiguity regarding the window for proposal submission. It is hence desirable to have a single window proposal submission forum. This initial central point / agency should identify the lead and partner funding agencies and forward the Concept Proposal to them for further consideration.

Evaluation: It is suggested that the lead funding agency set up a Scientific Review Committee for each MSP consisting of national and international experts and representatives of the funding agencies that will review the proposal through its various stages. It is important that the review process is completed in a timely manner.

6.2 Funding

A successful MSP would need sustained funding over the entire duration of the project covering all the way from the initial conceptual phase to the design development, construction, operation and maintenance phases.

Funding cycles are often much shorter than the life cycle of an MSP, leading to uncertainties and undesirable effects on the project implementation. It is therefore suggested that the project funding be approved for its total projected cost and duration, extending through the various phases of the project.

6.3 Management and Evaluation of Projects

For the success of any project, it is important to have a well-defined project management structure that ensures effective management and execution of the project through well-defined rules and guidelines. Periodic evaluation of the progress of the project is another essential aspect. Additionally, it is extremely important to ensure availability of financial and other resources throughout the duration of the project in a timely manner. Provided below are some general thoughts that may lead to effective management and success of mega projects.

- The multi-organisational nature of an MSP makes it important for all projects to have a Nodal Institute, with all other participating institutions having an MOU with the Nodal Institute for smooth execution of the project. A Project Coordination Center (PCC), with sufficient administrative and financial autonomy, should be hosted at the Nodal Institute to enable effective implementation of the project.

- All projects may be managed at various levels by two committees.

  A Project Management Board

  - The Project Management Board (PMB) will establish a framework for planning, implementation and review/monitoring of the progress of the project on a regular basis against financial, technical and schedules milestones and aspects of risk management.
  - The PMB will be fully accountable for scientific gains, manpower training, finance management and meeting project schedules.
  - For smooth functioning, the Project may also choose to have other committees with members drawn nationally as well as internationally. These committees will be constituted by the PMB, as required, from time to time.

  An Apex Oversight Committee (or Executive Council)

  - The Apex Committee (AC) will have oversight on all aspects of the project.
  - The AC will consist of representatives of funding agencies and scientists and engineers of repute.
  - In the case of National Mega Projects, the AC will also have members drawn internationally.
  - The AC will organise regular performance reviews of the whole project.
  - The AC will ensure timely release of allocated funds for the project.
  - In the case of international projects, the AC will appoint representatives on the international project management board.
  - For ease of execution of the project, the AC shall be empowered to approve specific rules and guidelines for procurement, hiring, payments, etc.
  - For smooth functioning of the project without undue interference and delays, it is crucial that the AC grants adequate financial and administrative empowerment to the PMB and PCC, keeping in mind that freedom and accountability go hand in hand.

- The Project Coordination Centre (PCC)

  - The PCC will maintain appropriate liaison, in context of the project, with all partners (including industries) and stake holders of the project and the funding agencies.
  - A Programme Director, will be the coordinator of the project, and will be the in-charge of the PCC.
  - The Programme Director will implement the PCC programmes in accordance with the rules and guidelines framed for the Project and other applicable Government of India rules, procedures and guidelines.

- The Programme Director shall have technical, administrative and financial powers and control in matters of the PCC as delegated by the PMB and AC.
- In the case of multi-national projects, PCC will be the responsible body for providing appropriate in-kind contributions over the duration of the project.

- Science Advisory Committee
  - It is important for any project to have a Science Advisory Committee (SAC) which will periodically evaluate the science and instrument requirements of the project. This committee, which will function under the PMB, will also be responsible for organising/initiating discussions on the science that can be done with the facility through various scientific committees, workshops, conferences. The SAC will also build the community of potential users of the facility through schools and workshops, thereby building scientific capacity in the country.
- Outreach and Public Engagement Committee
  - Science outreach is an important component of any mega science project and plays a crucial role in capacity building. Every mega project should ensure that sufficient resources are allocated for this activity.
- Fund Management
  - PCC will maintain a Separate Account of all receipts and expenses related to the project.
  - PCC will prepare its budget and submit this to the AC for recommendation each year.
  - Approvals for cost and time overrun of the project will be based on submission of detailed proposal by PCC and recommendation by the AC.
  - PCC should be sufficiently empowered to manage the fund distribution within the MSP partnership.
- Legal Support
  - In case of Mega Projects with international collaboration it is also important to have legal support throughout the duration of project that will address partnership and workshare issues, contracts with industry partners, and other project-related matters.
- A&A Mega Projects Consortium Committee
  - It is desirable to have a Mega Projects Consortium Committee that will enable sharing of scientific and technical resources. This committee can also enable formation of panels of technical experts and industrial partners from which resources for the various projects can be drawn.
- Data Policies
  - It is desirable that the data generated from large science projects be available as user-friendly data products that can be utilised by any scientist or student interested in doing so. Proprietary periods should therefore ideally be kept at a minimum, and nation-wide usage of data should be encouraged to maximise science outputs and visibility of these major investments.

7 INDUSTRY-ACADEMIA COLLABORATION

The extent of technology required for the advancement of scientific knowledge necessitates a strong collaboration between academia and industries. Mega Science Projects being an integral part of this whole framework, have very strong dependency on long-term partnerships between academia and industries. Effective use of advanced and cutting- edge technologies are highly required for capacity building leading to excellence towards astronomy-based mega science projects. Sharing available resources, benefits and risks by generation of ideas, prototyping, innovations etc. will be able to enhance the productivity towards large/mega projects in astronomy. Industrial involvement is also important to produce high-precision components in large quantities. As a spin-off, such R&D synergy between industries and academia would not only be able to provide more job opportunities but also translate the technology into products for societal benefits, both nationally and internationally.

The ongoing mega projects are examples where partnerships and collaborations with Indian and foreign industries are going on at a large scale. For example, India's in-kind obligations to the TMT project, in both hardware and software related aspects, are being executed through partnerships with industries. The research institutions involved in the project are working with large industries and MSMEs in the country, in close coordination with the TMT Project Office, to understand the requirements and manufacture hardware components through technology transfer and other collaborative methods. India is now in a situation to supply the full sets of high-precision components of the primary mirror of the TMT only because of long-term prototyping exercises carried out with several Indian industries over the years. Likewise, a team from NCRA along with industry partners led the design effort from initial concept to the successful final critical design review for the Telescope Manager System of SKA Phase-1, an end-to-end observatory management system that will be the brain and nerve centre of the entire, distributed observatory. For LIGO-India, one of the largest ultra-high vacuum systems of the world needs to be built, which will of course be unimaginable without industry-academia partnerships. The partnership has already led to the design and build of prototype high vacuum chambers. In a similar way, for other ongoing and planned mega projects in astronomy, academia-industry collaboration will be one of the key components that will enable pursuing front-line science using cutting-edge technologies.

The experience and skills gained by the industries associated with the mega science projects will be very useful not only for future astronomy projects in the country, but also in the manufacture of high precision engineering, opto-mechanical and electro-optical systems that have applications beyond astronomy, such as in defence and healthcare. A few industries have already benefited through their association with large astronomy projects in the past. These have been in the areas of thin film coating and vacuum technology, control systems software, high precision optical components, database management software, etc. These are summarised in detail in Table A3 (Annexure) that provides a list of Indian industries associated with the ongoing mega projects. This table also provides their exact involvements in the projects.

The industry-academia collaboration developed through astronomy projects can be leveraged to lead to public-private partnerships (PPPs) in niche areas in the country like education technology (design and manufacture of small telescopes and instruments), providing R&D services in emerging technology areas, etc. Also, some unique technology and facilities available with the research centres, such as those for detector and instrument control systems, laboratories for space instruments and manufacture of large optics, etc., can be shared with industrial partners. Such a synergy between industries and academia will enhance the nation's growth and enable the whole ecosystem to be globally more competitive. Such joint R&D activity will also help generate a set of academics who are industry compatible or employable.

8 THE INDIAN A&A COMMUNITY: STRENGTHS AND FUTURE OUTLOOK

The Astronomy & Astrophysics community is on a rapidly growing curve and we expect this trend to continue. To provide some background, we quote from the executive summary of the Decadal Vision document prepared almost twenty years ago in 2004 under the aegis of the Indian Academy of Sciences: “The committee is of the view that under the prevailing conditions and circumstances, it would not be desirable or profitable to undertake the construction of a large observing facility. Instead, the priority during the next decade should be to consolidate the existing facilities and, at the same time, groom the next generation of astronomers who would, in due course, take the next major initiatives.” The prevailing conditions referred to were the then small size of the community and sub-critical numbers in most areas. The vision to strengthen the community and then embark on more ambitious projects has since then been successful. Involvement of industry in many projects has also given a boost to these efforts. This growth in the last decade has been spurred by participation in mega projects. A related aspect is the addition of Astronomy & Astrophysics groups in more universities and many IISERs and IITs.

The present strength of the A&A community stands at about 500 researchers with a regular position in an established organisation. In addition, there are over 100 post-doctoral fellows and 600 Ph.D. students, all spread over more than 80 research institutions and university departments across the country. The growth of the community over the years is also clearly reflected in the increasing number of participants at the annual meetings of the Astronomical Society of India (ASI). Further, the past few years have seen an increase in the proportion of young researchers, increasing to about 70% during the 2023 annual meeting (as shown in Figure 12). It is also important to note the influence of the availability of world-class observing facilities on the growth. For example, the number of individual authors from India in AstroSat papers stands at around 530, with many of them from outside the conventional astronomy centers.

To further illustrate the growth, we consider the data on publications from India in journals where research in astronomy, astrophysics and associated fields is published. Note that this has overlap with fields like astro-particle physics and theoretical high energy physics, and hence some mixing with these other fields is present in this data. This is shown in Figure 13 where we see that there has been a rapid growth in the number of publications in A&A in the last 25 years. Number of publications is not the only parameter, it is important to see how these are being received by the larger community. Figure 14 indicates that the *h*-index of astronomy publications from India has grown by a factor of four since 1997. This is for same set of publications shown in Figure 13. We see that out of the approximately 1000 publications in 2015, more than 70 publications had more than 70 citations by the end of 2020. Thus, the number of well-cited publications from India has also increased significantly over the years.

It is also of interest to see whether the growth of publications is vertical, wherein the older centres of research contribute most of the publications, or whether there has been horizontal growth also with new centres coming up. A study of contributed papers from the Astronomical Society of India meetings in the last ten years shows that the number of distinct affiliations from where contributed papers originate has grown significantly. A number of university departments, IITs and IISERs have formed astronomy groups during this time. The share of these new groups to contributed papers in the annual meetings of the Astronomical Society of India, as well as in best paper and best thesis awards is growing. This is encouraging as it indicates not only the formation and growth of new centres, but also that they are contributing quality research.

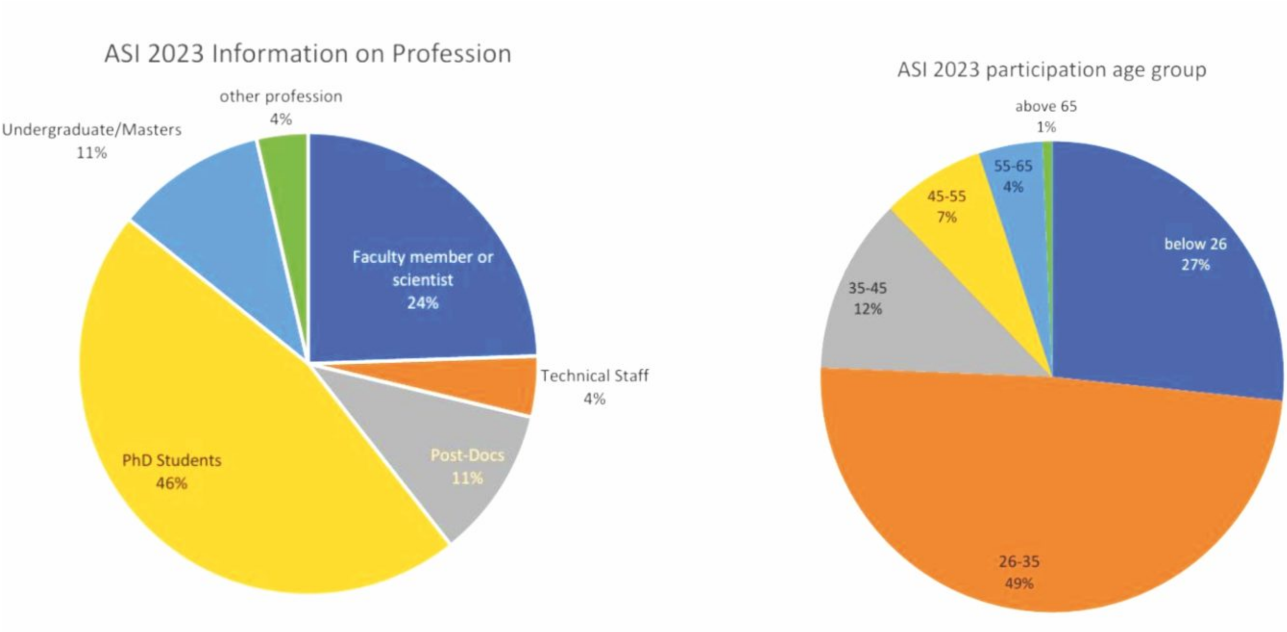

Figure 12: *Demography of participants at the 2023 annual meeting of the Astronomical Society of India.*

A recent analysis of contribution to research by DST-funded institutes shows that astronomy and astrophysics is one of the top three areas by number of research papers published in high-quality peer reviewed journals. The same report shows that two of the top five journals where Indian authors are cited the most are from this area. These numbers are from the Clarivate analysis of research publications from DST institutes for the last decade (2010-2019).

The number of authors who contribute papers in the annual meetings of the Astronomical Society of India has doubled in the last five years. This too indicates that the growth in the astronomy community is commensurate with the requirements of the mega projects like TMT, SKA, LIGO, etc. Eventually, we require an ecosystem where teaching and research in astronomy and related areas are practised in a large number of universities, colleges and institutions like NITs, IITs and IISERs so that the enthusiasm of students for these areas can be channeled to a career option. This can also help in ensuring a supply of well-trained students for the many cutting-edge programmes discussed in this document. The various facilities that have been developed and operated, the use of large databases and modelling have all led to human resources trained in not just research in A&A, but also in other skill-sets such as in the areas of thin film coating on large optics, design and fabrication of high-precision opto-mechnical components, design and development of precision optics and control systems for telescopes and astronomical instruments. These skill sets can be utilised in other areas also.

8.1 Capacity Building Plans for the Future

The total number of active professional astronomers in India (published at least one paper in the last two years) is more than 600. Of these, close to half are in astronomy research institutes like IIA, ARIES, PRL, IUCAA, NCRA-TIFR, while the others are in smaller departments in more general institutes like TIFR, IISc, RRI, IISERs, IITs, NISER, and

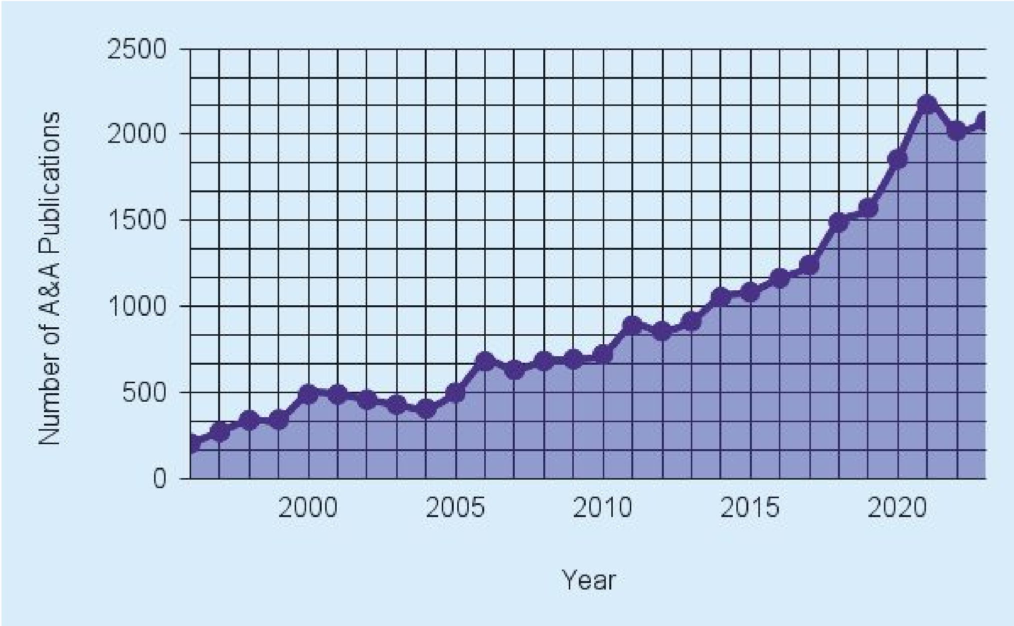

Figure 13: *Growth of Publications in Astronomy and Astrophysics from India. This is taken from the Astrophysics Data System and uses peer reviewed publications from the set of astronomy journals in the database. A rapid increase in the number of publications can be seen over the last two and a half decades. We see that the number of publications has doubled every eight years in this period.*

many universities like Delhi University, Jamia Millia Islamia, JNU, Osmania University, Pt. Ravishankar Shukla University, Panjab University, Presidency University (Kolkata) and several central universities etc. This number has grown considerably in the last two decades, with the growth in number of astronomers in research institutes, as well as a gradual increase in the number of astronomers working in universities and other educational institutes. We can expect a steady growth in future but, to ensure high quality, it is essential that a number of steps be taken. These are in addition to the various proactive measures in place already. *It is strongly recommended that a fraction of the mega project funds be dedicated for capacity building, training and outreach activities.*

8.1.1 Support for Research

It is important to set up processes to ensure that we are able to exploit developments in technology and sciences and any windows of opportunity that may arise from time to time. Some actions are suggested here. While many of them may already be in place, these activities are required to be enhanced and spread across more institutions.

- Support PhD students and Post Doctoral Fellows under mega projects. Well-funded (named) fellowships associated with each mega project may be set up to host high quality research and post-doctoral fellows. At least half of the positions should be for working in universities, IITs and IISERs.

- Provide training through trainee programmes in both research and technical areas.

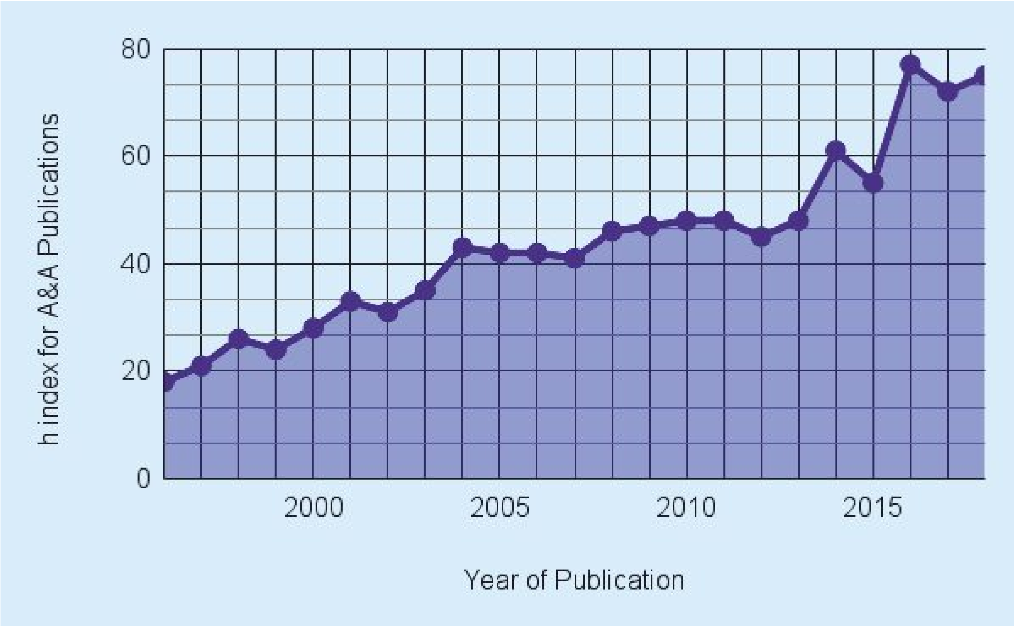

Figure 14: *Impact of astronomy publications. We have plotted the* h-index *for publications in Astronomy. This is taken five years after the year of publications. The x-axis shows the year of publication and the y-axis is the* h-index *after five years for these publications. This is a measure of how the publications are being viewed by the larger community. In general the* h-index *is expected to be a slow but stable indicator of citations as it is not influenced by outliers. We see that the* h-index *measured after five years has increased by almost a factor of four since 1997. Note that we are considering citations five years after publications and hence the last point is for 2018.*

- Provide funding for instrument or technology development as a part of participation in mega-projects.
- Encourage and support participation in national and international workshops and conferences.
- Support projects accepted for use of the facilities. Initiate and support programmes that will make use of archival data generated. For instance, ISRO provides support for successful proposals to utilise archival AstroSat data and this has had a very positive impact on the usage of the data.
- Conduct national-level workshops in focused research areas that will encourage the community to think of the science and required instrumentation, as well as prepare the community for efficient use of the facilities.
- Encourage collaborations in focused areas. Support small workshops in areas that require inputs from diverse disciplines to develop expertise in the country.
- Encourage interdisciplinary workshops. For instance, workshops that involve experts from associated disciplines like fluid dynamics, atomic theory, particle physics, engineering (for instrumentation), computer science, machine learning, etc., can be supported to enhance expertise and develop interdisciplinary linkages.

- Encourage training programmes in emerging areas that may lead to development of new methods or technologies and synergy with other initiatives like the quantum mission and the initiatives to encourage use of machine learning.

8.1.2 Training Programmes

Training programmes can be considered at two levels: (a) at the research level, and (b) at the graduate (post-graduate / Ph.D.) and undergraduate levels. Some suggestions for these are provided herein.

At Research Level

- Strengthening of graduate school programmes like the Joint Astronomy Programme hosted at IISc Bangalore. This programme was initiated jointly by IIA, IISc, ISRO, PRL, RRI and TIFR with students choosing to work in one of the institutes after completing course work and a project. Likewise, the joint pre-PhD coursework conducted by IUCAA and NCRA allows participation of PhD students from universities across the country.

- Yet another interesting programme has been the Integrated M.Tech-PhD programme in Astronomical Instrumentation conducted by IIA in collaboration with Calcutta University. This programme has led to human resources with skill-sets to develop facilities as well as do research, a combination best suited for mega projects.

- IIST-Thiruvananthapuram, has a variety of programmes aimed at training students for the Indian space programmes. This can be extended beyond IIST.

- Experience in online teaching gained in recent times can now be used to open up courses from these graduate programmes to PhD students all over the country. A suitable plan for evaluation can be developed.

- Make self-learning material available to PhD students and young researchers interested in research in astronomy and related areas using portals like SWAYAM.

- Regular organisation of schools and workshops in Astronomy & Astrophysics, like SERB Schools.

At Graduate and Undergraduate Levels

- An important point to note is that universities, IITs and IISERs contribute students to the graduate programmes in research institutes. Many universities, IITs and IISERs also have a thriving graduate programme in A&A. Therefore it is very important to strengthen the entire network of centres that contribute to research in A&A.

- To attract more students to astronomy, offering electives on astronomy in universities should be encouraged. At present such electives are being offered in a small number of universities and institutes, e.g., Delhi University, Pandit Ravishankar Shukla University (Raipur), Presidency University (Kolkata), Bangalore University, IIT-Indore, etc. IUCAA has recently (from the year 2021) started an M.Sc programme in Astrophysics in collaboration with the Savitribai Phule Pune University. Pondicherry University has recently started offering astronomy as an elective in its M.Sc (Physics) programme in collaboration with IIA. IUCAA, in consultation with senior astronomy faculty in different universities, has designed A&A course syllabus for short and long term programmes. IIT Indore has an MS programme in Astrophysics and Space Sciences and IISER Kolkata has a Centre for Excellence in Space Sciences. IISER-Mohali offers minor programme and Ashoka University has recently started the same at the undergraduate level. This needs to be expanded to more universities. Departments where multiple astronomers are present can be encouraged to offer a suite of electives or a minor.

- Faculty members of institutes and universities with experience in teaching astronomy courses can be encouraged to offer courses on online portals as well. It is heartening to see that the number of such courses on SWAYAM has increased in the last two years but more effort is required in this direction.

- Encourage universities and colleges to recruit faculty members in astronomy. Indeed, astronomy should be recognised as an essential field within physics just like high energy physics or condensed matter physics. Further, many areas of classical physics are used much more heavily in astrophysics and hence are better suited for teaching such subjects.

- Help set up small optical and radio telescopes with basic backend equipment in universities and colleges (with a goal of about 15 such facilities across the country over the next decade). In places where these are put to good use, more funds may be provided for better equipment and backend detectors. As evidenced in the special session on astronomy education during the ASI meetings, this can help generate manpower with a good grasp of basics.

- Encourage development of low-cost equipment that can be used in lab courses and projects in colleges/universities and demonstration of key innovations used in mega projects. Some of the equipment can be developed by the teams working on mega projects. Proposals for designing such equipment may be invited from the larger community. Users should be encouraged to write articles describing these experiments in journals of science and astronomy education so that the ideas can be replicated in other colleges and universities. As A&A mega projects require a variety of inputs, we should try to involve as many different departments and disciplines as possible in this activity. Industries that are participating in mega projects can also be tapped for support. The SWAN (radio antennas) and the solar spectrograph projects are a couple of examples of such development.

- Short duration (3-4 days) workshops on A&A should be organised in different colleges and universities. Such workshops are already being organised by a few institutes, and these need to be expanded. These workshops need to have an enlarged scope to cover skill-sets from physics, data analysis, engineering and management to train students for working in large projects.

- Hands-on training for selected students at large facilities associated with mega projects. Such facilities should also host students for semester-long or year-long M.Sc./B.Tech. projects and arrange for continued interaction with project students through online meetings and follow-up projects.

- Setting-up of advanced labs in educational institutions, sponsored by, and associated with, mega projects. This is essential to prepare the next generation of scientists and technologists.

8.1.3 Diversity and Inclusivity

Special efforts should be made to make the A&A community in India more diverse and inclusive, within the framework of prevailing guidelines and laws of the country. Some steps could be:

- Organisations should make necessary structural and cultural changes to be more inclusive, and to support and promote diversity.
- Equal opportunity should be ensured for women, differently-abled and marginalised sections with suitable mandates for optimal representation in all decision-making bodies, including selection and evaluation committees.
- Organisations should be encouraged to promote talented women scientists to leadership positions to create inspiration for young women aspiring to pursue A&A.

8.2 Public Outreach

As a part of our Scientific Social Responsibility (SSR), disseminating knowledge and experiences to younger generation is one of the important goals. Astronomy being a fascinating subject is highly capable of developing scientific temperament at various levels in the society. This unique aspect of astronomy must be utilised extensively at different levels in the society to strengthen scientific temper through education, research and various other methods. In the country so far, with help of various science centers, planetariums and through forums like National Council of Science Museums, we have been able to connect to the society at large. However, taking advantage of many ongoing and upcoming Mega Science Projects, we should attempt to make it more streamlined, focused and in synchronisation with international standards considering the scientific requirements of the society during the coming decades. One such effort has been the Vigyan Samagam (2019-2020), a year long touring exhibition of Mega Science Projects. The National Education Policy-2020 has also stressed upon dissemination of knowledge through outreach activity for larger societal benefits.

Outreach has many aspects. We have tried to outline some of these below. One common factor is that we should try to reach out in the local languages where possible. The Public Outreach Committee of the ASI and its network can be used to identify resource persons who can help with content creation and translation.

- Dissemination of research work and progress in Mega Projects. This can be in the form of press releases and audio-visual material to highlight key results and achievements in a simple language. Sharing these on social media. PhD students and post-docs should be encouraged to develop skills of content creation for outreach.

- Connecting with school/college students and tapping the latent interest in astronomy. This can be done through talks by astronomers and others involved in mega projects.

- Setting aside funds for small telescopes (not only in optical but also in radio and other wave bands) and instruments to be made available to schools for hands-on projects.

- Encourage astronomers to come up with ideas for citizen science projects. Set aside funds for such activities. These are particularly popular with school and college students. The Rad@home (https://radathomeindia.org/about-us) project is already doing this in the country with a primary focus on radio astronomy using existing facilities such as the GMRT. Citizen science astronomy is also being conducted under the Pune Knowledge Cluster project. Such projects have considerable scope and potential for expansion to other domains of astronomy as well as to bigger facilities like the SKA, TMT, LIGO, etc.

- Organise hackathons of the kind LIGO and SWAN projects have been running to provide short-term focus for groups of college students.

- Most observatories have arrangements for visitors. Some observatories and institutes (e.g. VBO, IIA) have the visits streamlined so that school/college groups can make online appointments for such visits in advance. This needs to be expanded to all observatories.

- Support planetariums for developing programmes related to work being done in India, and also to mega projects. Many planetariums run very successful outreach programmes and these can also be supported.

- Setting up science centers in different universities displaying models, various discoveries, audio-visual material on the Mega Science Facilities and the Science done with them, etc.

- Each mega project should have a formal interface to interact with the local population in the region. This should include efforts to support education in the region at all levels as well as for astronomy-related activities that may generate employment, e.g., astro-tourism.

9 SYNERGY WITH OTHER RESEARCH AREAS

Astronomy & Astrophysics research utilises basic understanding from diverse areas like physics, chemistry, biology, statistics and simulations using advanced computing techniques etc. The observational facilities, data management, processing and analysis also utilise a wide range of advanced technologies. Thus it is natural to expect that advancements in astronomy & astrophysics research will have huge implications for research programmes in other areas, and vice versa. Here we flag some areas of synergies with other research areas.

9.1 Laboratory Astrophysics

With the advancement of technology to conduct complex experiments in laboratories and for basic understanding of different astrophysical phenomena, the community has realised that it will be possible to recreate certain astrophysical conditions in the laboratory in a controlled manner. For example, creating a Big Bang like situation by colliding gold particles at super-high speed in ion colliders, or growing dust particles in a low density environment to understand cosmic dust etc., are very useful for advancing our understanding of various astronomical observations. Such experiments are referred to as "Laboratory Astrophysics". These laboratory experiments not only allow us to understand various known astrophysical conditions better but also allow us to simulate many astrophysical conditions not understood so far in terms of known models of physics. As understanding astrophysical phenomena requires a multi-disciplinary approach, laboratory astrophysics will cover a wide range of subjects like nuclear astrophysics, atomic physics, astro-chemistry, astro-biology and high energy astrophysics and plasma experiments.

The importance of laboratory astrophysics and related multi-disciplinary studies goes beyond understanding just the cosmic evolution. Advancement in materials science has enabled the development of many new detectors capable of working at different wavelengths to detect very faint astrophysical signals. Developments in the field of computer science have made us capable of simulating various physical conditions to understand the astrophysical phenomena in great detail. Considering the overall scenario, laboratory astrophysics is an emerging multi-disciplinary area.

9.2 Laboratory Plasma Physics

Laboratory plasma physics, for example with plasma confinement devices, is expected to play a critical role in fusion plasma as a source of energy and there is a strong synergy between this field and plasma astrophysics and magnetohydrodynamics in the context of solar plasma and beyond. Such studies involving both numerical simulations and laboratory plasma experiments will benefit both plasma astrophysics and India's involvement in the International Thermonuclear Experimental Reactor (ITER) project, which focuses on replicating fusion processes in the Sun for energy production on Earth.

9.3 Nuclear Astrophysics

Some of the most fundamental questions in science that are related to nuclear reactions inside stars, sequence of stellar evolution, nature of the first stars and their nucleosynthetic signatures, and the origin of elements can only be addressed using multi-disciplinary collaborative research between nuclear physicists and astrophysicists. While theoretical studies in the area of nuclear astrophysics have been undertaken, laboratory nuclear astrophysics is an area not yet practiced in the country. Institutions such as BARC, TIFR, SINP, VECC, IUAC etc, however, do have facilities that can, in principle, be used for laboratory nuclear astrophysics. The available accelerators and ion-beam research facilities provide the basic infrastructure and human resources to study nuclear reactions and nuclear processes of astrophysical relevance.

As a natural consequence of the relatively large funding towards mega projects like LIGO-India, TMT, SKA, and FAIR, it is quite timely to establish dedicated laboratories where the proposed science goals could be simulated under controlled environment with the given theoretical inputs. FAIR is one of the best examples having many experiments related to nuclear astrophysics under NUSTAR/R3C and other experiments where India could contribute significantly towards many unsolved aspects of astrophysical problems. The proposed Free Electron Laser (FEL) at IUAC will be able to provide high quality electron beams for producing THz radiation and understanding various physical processes and their applications. These FEL studies could be further extended to develop facilities like femto-second two-beam Peta-watt class lasers which could be used to understand various astrophysical processes. In early 2018, the Gemini Laser, the world's most powerful femto-second laser was used to produce relativistic electron-positron beams and get a mini gamma-ray burst in the laboratory for the first time. So, it is obvious that the need of future is to extend laboratory set-ups to conduct front-line astrophysical experiments in controlled laboratory environments to understand astrophysical phenomena.

9.4 Astrochemistry

The role of molecules and dust in the Universe is very important, be it in star formation in dense interstellar regions, dynamics within interstellar clouds or circumstellar shells of evolved stars, atmospheres of exoplanets etc. Spectroscopic identification of atomic or molecular species in space require affirmation from terrestrial laboratory observations. Identification of Fraunhofer lines and their attribution to hot atoms by Kirchhoff and Bunsen is among the first examples of this laboratory-astronomy connection. With advanced astrophysical observations several molecular species and radicals have been detected in different astrophysical environments. Currently there are more than 200 molecules confirmed in the interstellar and circumstellar medium. These observations provide crucial information regarding the physical and chemical properties of the object under observation. Observations of a group of emission lines in the mid-infrared spectral region indicate the presence of poly-cyclic aromatic hydrocarbon (PAH) family of molecules The relative variation of intensity between these emission features can probe the astrophysical environment and distinguish between early and late stages of stellar evolution. Crucial information regarding external galaxies and AGN are also studied through these mid-infrared emission features.

Understanding of the molecular spectrum through laboratory studies in conditions simulating astrophysical environments enables a better understanding of different astrophysical phenomena. Recent discoveries of primordial molecule HeH+ in NGC 7027 and aromatic molecules Benzonitrile and cyano-naphthalene in TMC-1 bring to the fore the importance of laboratory spectroscopic studies. In this context, a story worth mentioning is the laboratory confirmation of Fullerene cation as the carrier of two diffuse interstellar bands (DIBs). DIBs are unidentified absorption features in ISM that have remained a mystery for nearly a century. Two DIBs in the near infrared, at 9577 and 9632 Angstrom, were initially, in 1994, given possible attribution to electronic transitions in C60+. Confirmation was not possible as the available matrix isolated C60+ laboratory spectrum was broadened and wavelength shifted.

Twenty-one years later a laboratory spectrum in gas phase at low temperature clearly secured the first identification of DIBs.

Laboratory astrochemistry is not limited to spectroscopic confirmations. Experiments are also conducted to study chemical reactions and chemical evolution in shocks mimicking astrophysical conditions. In extreme vacuum like conditions of ISM, gas phase interaction for formation of molecules is rare. The abundance of hydrogen molecule can only be explained by considering grain surface reactions. Thus, laboratory studies of the effects of high energy radiation on the surface of minerals/dust grains gain significance. Astrochemistry provides the potential to elucidate the origin of biologically relevant molecules, their possible evolution in solar system like bodies and enables us to decipher the emergence of life on Earth.

Laboratory astrochemistry helps address the photo-physics, chemistry and science of cosmic dust. For these complex experimental set-ups, sophisticated instrumentation is required to mimic astrophysical conditions. Concepts like cryogenic storage, synchrotron and free electron laser set-ups require multi-institutional efforts. Considering the scientific importance, efforts are required to foster initiatives in this area over a period of time.

9.5 Quantum Enhanced Technology

Several countries in the world, including India, are advancing on cutting-edge quantum enhanced technologies (QETs). India's National Quantum Mission's thrust is in the domains of Quantum Computing, Quantum Communication, Quantum Sensing & Metrology and Quantum Materials & Devices.

QET is already in use in A&A. Calibration of astronomically observed spectral lines with unprecedented accuracy is possible due to the availability of ultra-stable, sub-Hz line-width optical frequency combs. Termed as “astrocombs”, this technique is used for high-precision wavelength calibration that enables high-precision radial velocity measurements such as required for exoplanet studies. Atomic clocks are being used for time and phase synchronization of geographically distributed (locally and intercontinental) astronomical detectors (e.g. radio telescopes, OPTICON, VLBI, GW detectors). Squeezed light is being used in the Advanced LIGO detectors to reach noise levels below the standard quantum limit, enhancing their sensitivity. Developing a frequency-dependent squeezer for LIGO-India will lead to similar sensitivity improvements and will also help in maintaining the LIGO-India detector at the same sensitivity as the other two LIGO-USA interferometers to maximize the science outcome. As part of LIGO-India pre-project activities the technology for ultra-narrow linewidth laser systems has been developed, which is a key step towards the development of high-power squeezed light sources.

Time and frequency transfer technology for precision time metrology was used in the Event Horizon Telescope for real-time imaging of the black hole in M87 and Milky Way galaxy, demonstrating the use of synthetic aperture imaging for radio frequencies. The use of quantum (optical) clocks will enable synthetic aperture telescope in the optical that will enable very high spatial resolution imaging. Theoretical and laboratory efforts are already on globally to study the use of the principle of quantum entanglement to share photons between observatories, leading to 'quantum telescopes'. In the future, highly-accurate electric-magnetic-RF sensors, gyroscopes, space-qualified optical clocks, single photon detectors and many more shall start a new era of precision-astronomy using quantum advantages of the devices. Quantum Computing is yet another QET that has promising applications in the areas of image processing of large format / large volume data sets and computational astrophysics.

India is already making considerable headway in the application of quantum technology in several areas such as developing techniques for quantum communication, development of quantum clocks, ultra-stable and sub-Hz line-width lasers/astrocombs and fiber-optic quantum links. All of these developments can be combined with the proposal of networking optical telescopes to build a prototype optical synthetic telescope, a technology that in the future can, in principle, enable the proposed NLOT to be part of a global optical synthetic telescope. It is important for Indian astronomers to develop interdisciplinary, international collaborations to begin development in this futuristic area of application of quantum technology in A&A. A key technology for the development of squeezed light sources is that of ultra-low loss optical coatings. At present, this technology is not available in the country and it is essential to develop the same through international collaborations. The technology of squeezed light used in GW detectors has ramifications for other QETs such as quantum computers, microelectronics as well as for experiments in fundamental physics.

9.6 Data Analytics, Big Data, Machine Learning and Artificial Intelligence

The last two decades have seen an (almost) exponential increase in the application of artificial intelligence (AI), machine learning (ML) and related techniques to almost all areas of human endeavour.

Analysis of data sets has always been an integral part of astronomy. However, the advent of digital sky surveys in the early 1990s brought in data sets on tera scales that demanded automation of data processing and analysis tasks. Large data sets from multiple surveys and large facilities (both ground and space) also saw the development of data archives and database systems that have evolved into global data grids providing access to data from multiple facilities. The growth in data volume and the need for value-added data products that can be used for follow-up research led to the application of Machine Learning (ML) techniques for aspects such as source detection, morphological and structural classifications. Some of the early works included those of astronomers from India, for example the application of neural networks in classification of stellar spectra, and separation of stars and galaxies. The wealth and growth of data volumes at increasing rates, together with the complexity of the data, are leading to increased use of ML/AI techniques to quickly discover features in astrophysical images, light curves and spectra, and to characterise, cluster and classify features, sources and populations. AI/ML techniques are also being employed to extract physical information from simulations, for example in estimating the amount of dark energy and dark matter (and their evolution) in the Universe, and disentangling the myriad effects of dark matter and dark energy. Yet another application is in the area of heliospheric science and space weather.

Application of AI/ML in astronomy is a growing landscape, with its scope also widening to data acquisition. AI systems can be trained to plan observations dynamically based on specified quality criteria. Such AI-based control systems can provide efficient planning, scheduling, and observing, leading to improved scientific outcomes in terms of both quality and quantity of observations. Facilities that can provide dynamic observing will be critical in the area of Multi-Messenger and Time Domain Astronomy wherein prioritisation of the follow-up of transient events by a number of different facilities becomes necessary. In the radio regime, real-time identification and flagging of transient radio signals due to radio frequency interference (RFI) is crucial, and this can be done effectively by employing AI/ML methods.

The usage of AI/ML techniques requires access to high performance computing and in the coming years there is a pressing need to combine data archives and virtual observatories with super computing systems so that very large data sets can be analysed at source and users do not have to transfer raw data or work with raw data on their computers. Much of the development in the application of AI/ML in astronomy is aided by developments outside astronomy, particularly in the field of computer science. We are seeing rapid developments on many fronts such as convolutional neural networks utilising deep learning for image classification, generative pre-trained transformers for text generation, and generative adversarial networks for text-to-speech, text-to-image and text-to-video applications. Efforts are on to develop a generalised AI, a system capable of performing a wide range of tasks at a human-level intelligence. These developments need to be followed, and such emerging technologies need to be adopted for research problems in astronomy. The large volume data sets available in astronomy will, in turn, aid these developments. There is considerable expertise available in the industry in the area of big data and AI/ML, that can be capitalised and harnessed by the research sector through systematic efforts.

10 SUMMARY AND RECOMMENDATIONS

International scientific communities periodically formulate Vision Documents to identify thrust areas of research and define priorities to make progress in science in an efficient and focused manner. In the year 2004, the Indian Academy of Sciences brought out a Vision Document for Indian Astronomy & Astrophysics for the next decade. It is gratifying and reassuring to see that several recommendations in that document have now been realised. The community has grown many fold. In addition, the Indian Astronomy community has embarked on several major international mega science projects that will put Indian astrophysics at the forefront of research and technology in the coming decades. All this makes the present moment the right time to put forward a comprehensive Mega Science Vision Document for Astronomy & Astrophysics extending to 2035.

Summary:

A basic introduction to this document is provided in Section 1. Section 2 of this document provides a pedagogical listing of various leading science questions that the astronomy community wishes to address in the coming decade. Subject areas covered include (i) fundamental physics, (ii) early Universe and Cosmology, (iii) galaxy formation and large scale structure, (iv) nearby galaxies, (v) Milky Way galaxy and its interstellar medium, (vi) cosmic chemistry, (vii) compact objects and black holes, (viii) transient and time-domain multi-messenger astronomy, (ix) exo-planetary science and (x) solar physics.

Some of the key questions that will be addressed using observations, numerical simulations and theoretical analysis in the coming two decades are the following: test of variance/invariance of fundamental constants; test of General Relativity, particularly, in the strong gravity limit, i.e., near compact objects and on extragalactic scales; the nature of dark matter and dark energy and their interpretation from a fundamental particle physics viewpoint; formation and evolution of galaxies and their relation with their central SMBH; launching, collimation and acceleration of powerful jets from the center of active galaxies; chemical evolution of our Galaxy; formation and evolution of cosmic magnetism, formation of star-planet systems; earth-size rocky planets located in the habitable zone of their parent star; solar activity and its impact on the space environments of solar system planets; astronomical transients and their follow-up observations that may open up significant discovery space for new astronomical/astrophysical phenomena.

Section 3 provides a summary of how the international community is planning to address the key astronomy and astrophysics questions in the coming decade. As the technical and financial demands are huge, most of the upcoming international projects are multi-national and multi-institutional in nature. Thus, it becomes imperative to be part of such consortia to be able to lead important scientific programmes. Even within a consortium, several important questions are addressed using (i) large dedicated survey facilities, (ii) "large observing programmes" with several tens of observing nights dedicated to a specific project and (iii) network of observatories operating at different wavebands located in different parts of the world and space. Thus, in addition to being part of a mega science project, it is important to have a clear plan to derive maximum scientific outputs. This Section also indicates some of the niche areas for the Indian astronomy community to make a significant impact.

Section 4 summarizes the status of national R&D efforts. First part of this Section provides a historical perspective and the scientific impact that the Indian community has made in different aspects of Astronomy & Astrophysics. The second part of this Section presents the status of different observatories in the country and their proposed plans for future instruments and upgrades. As the Indian astronomy community is embarking on different mega science projects, it is important that the existing observatories and instruments are maintained and upgraded efficiently to cater to the needs of the community at any given time. It is also important that efficient use is made of the facilities. A few suggestions that will enable efficient use of the facilities as well as provide ample resources for the growth of the community are provided at the end of this section.

In the last three decades, a significant fraction of research in Astronomy & Astrophysics has become a large global collaborative endeavor. This is because state-of-the-art observing facilities are expensive and technologically complex, and may only be built by multiple nations. Their efficient operation and usage require the joint effort of hundreds or thousands of trained researchers having different levels of expertise. Being a part of the large international collaborations of the upcoming observing facilities is imperative to be at the forefront of A&A research for the astronomy community of any country. Section 5 of this document summarises the upcoming mega projects (like TMT, SKA, LIGO-India etc.) in which the Indian community is a partner, and other mega science projects (like LSST, CTA and MSE) where India has some contributions. Highlighting the need for our own facilities to bridge the gap between the existing and proposed large facilities, the document lists various national large projects (NLOT and NLST) proposed by the Indian astronomers. The document also summarises the expected timeline for these projects and prioritizes them as per the plans of the community.

Continued commitment towards the mega projects (such as TMT, SKA and LIGO) in which India is already participating has been recommended with suggested mechanisms to maximize scientific, technical and other types of value-returns. In addition, priority may be given to indigenous facilities that use technologies learnt from participating in the international mega projects. Priority should also be given to indigenous facilities that will place Indian astronomy at par with the international community and/or open new windows that currently do not exist. Emphasis is to be placed on development of prototype instruments with new technologies that can eventually lead to development of instruments for the international mega facilities. There needs to be a focus on building an integrated data archive and distribution facility for all the astronomy resources in the country. Based on these considerations and the present need of the Indian astronomy community, a prioritized list of projects is provided. Astronomy being a multi-messenger and multi-wavelength science, it is important to have facilities for broad spectrum observations.

It is noted that most mega projects will require initial seed money for a pre-project phase for carrying out several activities such as (a) exploration and establishment of the nature of Indian contribution in the case of international projects, (b) laying down the specifications and design development, (c) prototype development and technology capacity building, and (d) development of project partnerships, work share agreements, etc. The quantum of the initial funding would vary from project-to-project and their specific requirements.

For the success of any project, it is important to have a well-defined project management structure that ensures effective management and execution of the project through well-defined rules and guidelines. The document (Section 6) also provides some general thoughts that may lead to effective management and success of mega projects. One of the key recommendations is to have a Mega Projects Consortium Committee that will enable sharing of scientific and technical resources between different projects. This committee can also enable formation of panels of technical experts and industrial partners from which resources for various projects can be drawn.

It is imperative that Indian industries are actively involved in fulfilling in-kind commitments towards various international projects and in building our own large facilities. The document highlights the ongoing successful industry-academia collaborations in different projects, and provides (in the Annexure) a list of the industries that are engaged with the mega projects.

The success of our country's investment in the mega science projects to generate high-impact scientific output depends on the size and quality of the astronomy community that will eventually use these advanced facilities. Section 8 of this document focuses on this aspect. Statistics presented in this Section clearly indicates a steady growth of the A&A community over the last two decades, as well as an increase in the number, and impact, of publications in national and international scientific journals. The achievements have been remarkable, considering the fact that the observatories, computing resources, and infrastructural facilities available to the Indian community are significantly fewer and smaller than those available internationally. The document strongly recommends that a fraction of the funds allocated for mega projects be dedicated for capacity building, training and outreach activities. With a focus on developing young work-force, the document lists several steps that can be taken at different levels (PhD, postgraduate and undergraduate, and school) to attract and train young students in Astronomy & Astrophysics and cutting-edge technologies. The document also emphasizes the need for keeping the general public up-to-date with the scientific developments. Various suggestions for achieving this are also provided.

The document highlights possible synergy between A&A and other research areas (Section 9). In particular, astrochemistry, and use of quantum technology, artificial intelligence and machine learning.

The funding (tentative) required for the various projects as well as for developing an ecosystem that will enable sustained and effective use of the mega facilities is indicated in the Annexure.

Recommendations:

For Indian astronomy to be in the same league as the rest of the world, it is important to have access to large observing and high-end computing facilities. This document makes several recommendations in this regard. The salient recommendations are provided here.

- It is evident from the discussions presented in Sections 3 and 4 that growth of the Indian community to a critical level is required in certain research areas (exoplanet science, transients, numerical relativity, realistic magneto-hydrodynamical simulations, large instrumentation and large data handling) to exploit the capabilities of the upcoming large facilities to the fullest.

- It is important for India to have access to the best multi-wavelength and multi-messenger observing facilities in the world, through international collaborations. In particular, it is important to be part of any evolving new research area or technology in the coming decades. This is very important to sustain the scientific ascendancy the community may gain from the mega projects.

- Continued participation in the mega projects India is already participating in is essential. For the success of these Mega Science Projects, it is important to adhere to all the commitments (monetary and in-kind contributions) and provide deliverables of the required quality and in the required quantities on-time over the full duration of the projects. In particular, striving to build large instruments as in-kind contribution will provide the much-needed technical know-how to our scientific community and industries.

- It is important to bridge the gap between the largest optical telescope (3.6-meter DOT) presently available in the country and the TMT that will be operational in a decade's time. Therefore, it is imperative that we develop our own 10-meter class facility and/or participate in other 10-meter class telescope projects. It is also recommended that the Indian astronomy community explores the possibility of being part of international consortia of observatories. This will enable access to a wide variety of telescopes and instruments.

- To utilise the existing national astronomy facilities optimally, it is important to upgrade and operate them efficiently. This document provides some suggestions in this regard. In particular, automation and networking of some of the facilities fitted with well thoughtout instruments will enable Indian astronomers take gainful advantage of the country's geographical location in areas of time-domain astronomy.

- With the successful launch and continued operations of AstroSat, India has joined the small league of countries operating space observatories. While the focus of the international community is shifting towards higher wavelength observatories in space, it will be important to plan and exploit the window of opportunities in other wavebands (such as in UV and X-ray) in space to make unique contributions.

- Solar astronomy facilities in the country have not seen any major developments for some time. While the recently launched Indian solar space observatory Aditya-L1 will provide a good impetus, a complementary ground-based facility is the need of the hour.

- It is now well documented that well-maintained data archives considerably enhance the scientific output of astronomical observations. It is strongly recommended that we maintain a centralised data archive for all the Indian facilities. Suitably structured data pipeline facilities are needed to provide nearly uniform quality processed data to the community.

- It is important to have large dedicated computing facilities to achieve maximum scientific outputs from various astronomical observations. In particular, more realistic simulations are needed to interpret data from large telescope facilities. Setting up a national computing facility that caters to the needs of all the mega-science projects will yield best results with optimum resources.

- It is important to build a community with expertise in astronomical instrumentation, that can build large, high precision instruments. As observatory-class facilities run for several decades, their continued relevance and success depend on instrument upgrades. It is important for the Indian community to be in a position to propose and build instruments with evolving technologies in the coming decades.

- A Mega Projects Consortium Committee may be put in place that will enable sharing of scientific and technical resources between different projects.
- An inclusive growth of human resources is essential for optimal use of the future facilities. We recommend that a good fraction of the budget for a mega science project be spent on this effort. While the past decade has seen good growth in the number of astronomers as well as the scientific output, there clearly is a need to enhance the level and broaden the geographical reach of organisations where research and teaching in A&A are undertaken. In particular, bringing A&A research and instrumentation to undergraduate and postgraduate teaching institutions (such as in countries like the USA) is very important.
- Translation of scientific outcomes to evolve technologies for societal benefits and dissemination of the scientific outcomes should be an important and integral part of all mega science endeavours.

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ANNEXURES

Table: A1 *Funding Requirements (Tentative) for Mega Projects*

Project	Status	2020-2025	2025-2030	2030-2035
OPTICAL & IR				
1. TMT#	International (10%) National	Rs. 125.3 crores	Rs. 763.1 crores	Rs. 250.6 crores
2. NLOT+	National	Rs. 100 crores	Rs. 750 crores	Rs. 1000 crores
SOLAR				
1. NLST	National	Rs. 110 crores@	Rs. 552 crores	Rs. 25 crores
RADIO				
1. SKA Phase-1%	International (6-7%)	Rs. 575 crores	Rs. 600 crores	Rs. 350 crores
2. eGMRT	National	—	—	Rs. 150 crores
3. SKA Phase-2	International	—	Rs. 450 crores	Rs. 50 crores
GRAVITATIONAL WAVE				
1. LIGO - India	National	Rs. 2600 crores*		Rs. 100 crores
SUB-mm / TERA-Hz				
1. 15m Sub-mm Antenna (HSMF)	National	Rs. 25 crores	Rs. 300 crores	Rs. 10 crores
γ-RAY				
1. Second Generation Facilities (MACE-II & SCTArray)	National	Rs. 100 crores	Rs. 200 crores	Rs. 100 crores
1. CTA - Phase II	International	—	Rs. 100 crores	Rs. 50 crores

Table A1: Mega Projects Funding Requirements (contd.)
#: The current sanctioned amount for the TMT project is Rs. 1299.8 crores, of which Rs. 160.9 crores have been spent till 2020. A 30% cost overrun is expected due to delay in the project completion. +: Project cost of NLOT is estimated based on similar ongoing international projects. @: This amount is the projected NLST requirement for YY 2023-2025. %: Current sanctioned amount for SKA Phase-1 is Rs. 1250 crores. *: Current sanctioned amount for LIGO-India for completion of the project by 2030.

Table: A2 *Funding Requirements (Tentative) for Ecosystem Development Projects*

Project	Status	2020-2025	2025-2030	2030-2035
OPTICAL & IR				
1. Participation in international 8-10m class observatories	International	Rs. 30 crores	Rs. 30 crores	Rs. 30 crores
2. Network of small telescopes	National	Rs. 10 crores	Rs. 100 crores	Rs. 5 crores
3. Mauna Kea Spectroscopic Explorer	International	Rs. 5 crores	Rs. 5 crores	Rs. 480 crores (2031-2038)
4. NLOT - Second Generation Instruments	National	—	—	Rs. 10 crores
SOLAR				
1. NLST - Second Generation Instruments	National	—	—	Rs. 100 crores
COMPUTATIONAL REQUIREMENTS				
High Performance Computers	National	Rs. 200 crores		
CAPACITY BUILDING				
Technology and Human Resource Development (including telescopes for student training)	National	Rs. 200 crores		

Table: A3 *A list of selected industries that have participated in some of the mega projects*

Work	Industry	Remark
PROJECT: INDIA-TMT [NO. OF INDUSTRY PARTNERS: 43]		
Concept design of Vacuum Coating Chambers	Hind High Vac Company, Pvt. Ltd, Bengaluru	Associated with the astronomy community for over 20 years. Previous experience in building coating chambers for optical observatories in the country enabled their successful qualification.
Development of Observatory Server software modules	Thoughtworks Technologies (India) Pvt. Ltd., Pune	Designed and developed 3 modules
Development of telescope control system software modules	Honeywell Automation India Ltd, Pune	Prototype modules development
Primary Mirror Control Systems (M1CS): Edge Sensors	Optics and Allied Engineering Pvt.Ltd, Bengaluru; GOAL, Puducherry; ARCI, Hyderabad; Sahajanand Laser Technology Ltd, Gandhinagar; Mechvac India Ltd, Mumbai	Manufacture of precision electro-optics; thinfilm coating; etching. Prototype development helped GOAL in a successful bid for development of sensors for the SALT telescope.
M1CS: Actuators	Tamboli Engineers Pvt. Ltd., Pune; Southern Electronics, Bengaluru; Indo Danish Tool Room, Jamshedpur; Amado Tools, Bengaluru; AvasaralaTechnologies Ltd., Bengaluru	Prototype manufacture. Successful qualification for production (3 industries).

Work	Industry	Remark
Primary Mirror Segments: Segment Support Assemblies (SSA)	Avasarala Technologies Ltd, Bengaluru; Godrej & Boyce Manufacturing Company, Mumbai; IPA Private Limited, Bengaluru; Panch Dhatu, Bengaluru; Jindal Aluminium Limited, Bengaluru; Nucon Aerospace Private Limited, Hyderabad; Southern Electronics, Bengaluru; Lakshmi Technology And Engineering Industries Ltd, Kalapatti; Futuretech Engineering Private Limited, Bengaluru; Silvergrey Engineers, Bengaluru; Chakradhara Aerospace And Cargo Private Limited, Coimbatore; Larsen & Toubro Limited, Coimbatore	Prototype manufacture, manufacture of components, development of heat treatment manufacturing techniques for high precision components, successful qualification for production (L&T).
SSA Central Diaphragm	GTN Engineering (India) Limited, Coimbatore; MJ Enterprise, Vadodara; Prakash Engineering Work, Bengaluru; Therelek Engineers Pvt. Ltd., Bengaluru; Magma Machining Pvt. Ltd., Hyderabad; Techno Tools Precision Engineering (P) Ltd, Bengaluru; Central Tool Room And Training Centre (CTTC), Bhubaneswar; CMTI, Bengaluru; NCAIR, Mumbai	Development of heat treatment and manufacturing techniques.

Work	Industry	Remark
Fabrication of warping harness cables for SSAs	Amphenol Interconnect India Pvt. Ltd. Bengaluru; Sika Interplant Systems Ltd., Bengaluru; Trasccon Interconnection Systems Pvt. Ltd, Bengaluru	
India-TMT Optics Fabrication Facility	Epicons Consultants Private Limited, Thane; Arwade Infrastructure Limited, Pune	Civil works of the building
Primary Mirror Segments Polishing	Optics & Allied Engg. Pvt. Ltd., Bengaluru	Process development for hexing and pocketing
Primary Mirror Segments Polishing	S.R. Enterprises, Bengaluru; Furnace Designs & Manufacturing Co., Bengaluru	Design and manufacture of metrology tools; thermal chamber
Third Party Inspections	Tuv India Private Limited, Bengaluru; Akuva Infotech Pvt. Ltd., Bengaluru; Elite Metrology, Bengaluru; Carl Zeiss India Pvt Ltd, Bengaluru; SGS India Pvt Ltd , Bengaluru; CMTI, Bengaluru	

The experience and skills gained by the industries associated with the India-TMT project will be very useful for future astronomy projects in the country; and manufacture of high precision engineering, opto-mechanical and electro-optical systems that have applications beyond astronomy, such as in defence and healthcare.

Work	Industry	Remark
RADIO ASTRONOMY PROJECTS: eGMRT & SKA [NO. OF INDUSTRY PARTNERS: 5]		
Hardware development and refinement (eGMRT)	Tata Consulting Engineers, Pune	Associated with the GMRT project for more than 25 years, since the time of the original design of the GMRT, through various changes and upgrades to the mechanical structure of the antennas. The company has benefited significantly from the interactions over the years.
RF electronics (eGMRT)	Tantrayut Telecom Ltd, Pune	Associated since 2015 for design and prototype development of very specialised RF electronics. The company gained valuable experience that leveraged it to become a major supplier of advanced RF electronics for various sectors in India, including defence.
Firmware development for signal processing systems (eGMRT)	Nvidia, India	Associated for about 10 years, starting with development of the firmware for GPU-based next generation real-time digital back-end for the upgraded GMRT and following up with additional tasks for optimised routines for various radio astronomy applications.

Work	Industry	Remark
Software Development (eGMRT)	Tata Consultancy Services, Pune; Persistent Systems, Pune; Thoughtworks, Pune	Associated for 5-10 years. TCS: Development of next-generation systems for monitor and control and observatory-wide management systems. The company has benefited from this work to synergise their contributions to other major projects such as ITER and this has been a win-win situation for all concerned. Persistent: Developed the proposal handling tool and the data archive management tool for the GMRT. This work was leveraged for the development of similar tools for Astrosat and other projects. Thoughtworks: Development of aspects of software and algorithm development for radio astronomy applications such as optimisation of imaging pipelines for radio astronomy; use of ML/AI techniques in data analysis.

Work	Industry	Remark
Software Development (SKA)	Tata Consultancy Services, Pune; Persistent Systems, Pune; Thoughtworks, Pune	Associated for 5-10 years. TCS: initial design phase of the Telescope Manager system for the SKA, early prototype development work, active contribution to the construction phase of the SKA-1 systems. Persistent: initial design phase of the Telescope Manager system, early prototype development work, and contribution to the construction phase of the SKA-1 systems. Members of this company have grown to be assigned leadership roles in the SKA Phase-1 observatory software development team (e.g.the lead for the entire international SAFe releasetrain team) and are highly valued by the SKAO management. Thoughtworks: planning development of regional science centres for the SKA (as part of the SKA working group on this sub-system).

Work	Industry	Remark
PROJECT: LIGO-INDIA [NO. OF INDUSTRY PARTNERS: 5]		
LIGO Vacuum chamber prototyping	VacuumTechniques Pvt Ltd., Bengaluru	Actual size BSC and HAM chambers used at LIGO were fabricated to demonstrate indigenous fabrication of these components.
80K cryopump	Aditya High Vacuum, Kathwada	Prototype design and development for use in LIGO-India Vacuum system.
Beam tube Prototyping	Godrej & Boyce Manufacturing Company Ltd., Mumbai	Fabrication of 10-m beam tubes to establish the process of cleaning and vacuum leak testing of beam tube segments.
Vacuum System of 10-m prototype interferometer	RANVAC Technologies, Bengaluru	Vacuum envelope for the 10-m arm length prototype at RRCAT to serve both as a training facility and testing facility for LIGO-India.
Optics for 10-m prototype interferometer	Light Guide Optics Pvt. Ltd., Indore	Optics development for the 10-m arm length prototype at RRCAT.

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The Working Group of MSV-2035 (A&A) acknowledges the following for their inputs:

Poonam Chandra (NCRA)
V. Bhalerao (IIT-Bombay)
Kuntal Misra (ARIES)
D.K. Sahu (IIA)
Bhaswati Mookerjea (TIFR)
Sarita Vig (IIST)
L.K. Dewangan (PRL)
Manash Ranjan Samal (PRL)
Saurabh Sharma (ARIES)
Neelam Panwar (ARIES)
Jessy Jose (IISER-Tirupati)
Joe Philip Ninan (TIFR)
Maheswar Gopinathan (IIA)
Soumen Mondal (SNBNCBS)
Blesson Mathew (Christ University)
Tapas Baug (SNBNCBS)
D. Jagadheep (IIST)
B. Eswar Reddy (IIA)
T. Sivarani (IIA)
Abhirup Datta (IIT-Indore)
L. Majumdar (NISER)
Nirupam Roy (IISc)
B. Ramesh (RRI)
P. Sreekumar (ISRO/Manipal)
Sowgat Muzahid (IUCAA)
Ranjeev Misra (IUCAA)
Tarun Souradeep (RRI)
S. Rastogi (DDU, Gorakhpur)
R. Sridharan (IIA)
Dipankar Banerjee (ARIES)
K.Sankarasubramanian (ISRO)
B. Ravindra (IIA)
Durgesh Tripathi (IUCAA)
A. Raja Bayanna (USO, PRL)
Shibu Mathew (USO, PRL)
S.P. Rajaguru (IIA)
Sudip Bhattacharyya (TIFR)
K.P. Singh (IISER-Mohali)
Dipankar Bhattacharya (IUCAA / Ashoka University)
Aru Beri (IISER-Mohali)
Varsha Chitnis (TIFR)
Amit Shukla (IIT-Indore)
Pratik Majumdar (SINP)
Yogesh Joshi (ARIES)
Basudeb Dasgupta (TIFR)
Rishi Khatri (TIFR)
Girish Kulkarni (TIFR)
S. Majumdar (TIFR)
Avinash Deshpande (RRI /IIT-Kanpur)
Sendhil Raja S (RRCAT)
Subhadeep De (IUCAA)

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