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New age observing facilities for Indian astronomy: 2020–2035

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Abstract. In this article, we present the current state of observing facilities available for Indian astronomers in various wavelength bands existing in the country. We also mention a few state-of-the-art astronomical facilities across the globe and contrast them with the Indian facilities. We then present a vision for improving our facilities

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mega-science projects across the globe, (c) continued involvement in International projects, and (d) creating our large-scale facilities. These steps are divided into short, medium, and long-term tasks/projects. Recommendations for building large telescopes with versatile back-end instruments on Indian soil for Indian astronomers have been provided for each wavelength band. All these world-class astronomical observing facilities warrant cutting-edge technologies ranging from signal/image processing, high-performance computing, algorithms, and AI/ML. We hope this exercise will start a discussion and eventually lead to the initiation of these projects, which will result in significant scientific breakthroughs in the coming decades.

Keywords: Telescopes — UV — optical — IR — gamma ray — X-ray — radio — Submm — gravitational wave — observing facilities.

1. Introduction

We are living in an exciting era of exploration of the Cosmos. The upcoming decades in Astronomy and Astrophysics will broadly focus on discovering and characterizing new habitable worlds, exploring the transient Universe, and understanding the formation of galaxies and processes and the physical paradigm governing them. JWST's recent discovery of farthest galaxies (Wang *et al.* 2023), Event Horizons's image of the Blackhole (EHT Collaboration 2019) and discovery of Earth-like planets (Hu *et al.* 2024) in the recent times are a testimony to the investments made over the past decade bearing fruit in the areas mentioned above. Also, the six Nobel prizes related to Astronomy and the allied areas over the last decade have been made possible with the aid of enormous financial and human resources invested in projects like LIGO, CERN, Keck, etc., across the globe (see US Decadal survey 2020 report).[1] These investments and the fruitful discoveries indicate the direction of research in observational astronomy where cutting-edge instruments developed over decades are pushing the boundaries aiding in new understanding of the Cosmos.

With its large base of students and early-career scientists working in astronomy, India is yet to contribute significantly to many of these areas. Our students rely on small to medium telescopes and instruments for data collection or heavily depend on archival data. Although this research produces interesting results, it is commonly felt that the astronomical observations with the Indian facility are yet to make cutting-edge discoveries up to the level of outcomes from the peers working in some areas. We believe this is due to a lack of observing facilities with extraordinary capabilities, where the recent scientific breakthroughs from Europe, the US, and China came from significant investments in telescopes with transformative capabilities equipped with state-of-the-art instrumentation. Three principal strategies have been identified to bridge India's existing scientific and technical gap. These are: (A) Enhancing the current facilities. (B) Participate in mega-science projects across the globe while obtaining observation time on existing large telescopes through collaborations and (C) build large-scale facilities in the country.

To improve the current facilities with state-of-the-art instrumentation, recommendations are made in this article for upgrading existing observing facilities in the country in a phased manner over the next three to seven years. These recommendations are intended to improve the productive lifespan of the existing instruments, enhance the quality of the data, and improve the science that comes out of them.

Previous decades saw Indian astronomers coming together to push for partnering in large projects such as CERN, ITER, LIGO, SKA, TMT, etc. This has created immense opportunities for scientific and technical advancement (both in research institutes and MSMEs of the Indian industry) in the country because of the stringent demands that these projects impose. Such collaborations should continue for the country's scientific well-being and improve India's participation in solving all the important science questions of the next decade.

At institute levels, collaboration with the international community on small- to medium-sized missions and projects (both in terms of budget and time) will augment the technical capabilities of the respective institutes while also bringing them quality observing time on some of the existing advanced telescopes (e.g., SCALES project of IIA, RoboAO project of IUCAA).

While following these strategies, India should also build its large facilities, which the country is gearing up for. To implement the above plans, a clear picture of the currently available resources within the country in all wavelength bands needs to be identified, and the scope of strengthening these resources to make them state-of-the-art is also necessary. This article makes an honest effort in this direction. We hope such an effort will help the community start a discussion and reach a consensus on prioritizing various projects for better scientific returns in the upcoming decade.

[1] https://nap.nationalacademies.org/read/26141/chapter/2.

For ease of understanding of the existing facilities within the country, they have been classified as high-energy ground, high-energy space, UV-optical, infrared, radio, Submm, and gravitational wave Astronomy facilities. Along with these, efforts towards identifying better sites within the country for establishing newer facilities are also crucial. Hence, this article forms a separate section along with the above-mentioned classification topics, which are presented as sections. These sections are modular and complete, covering issues like next-generation observing facilities - world vision, existing facilities, projects over the next 3 years, projects over the next 3–7 years, and vision for the next 10 years, from the subsections. The summary forms the final section of this article.

2. High-energy ground-based astronomy facilities

The high-energy astrophysics research, carried out in India using ground-based instruments, aims to explore the non-thermal Universe in the energy range from tens of GeV to a few PeV. The research and development activities in this field involve both front-line observational and phenomenological studies and technological spin-offs. It also incorporates research in other complementary astroparticle physics topics like cosmic-ray and gamma-ray propagation effects, intergalactic magnetic field, particle acceleration and radiative processes, and signature of dark matter candidates. The journey of ground-based gamma-ray astronomy with the atmospheric Cherenkov telescopes (e.g., TACTIC, HAGAR, MACE) and particle array detectors (e.g., GRAPES) has been highly successful and satisfying over the last two decades. The TACTIC telescope has been operational at Mount Abu, Rajasthan, since 1997, whereas the MACE telescope started its regular science operations in 2021 at Hanle, Ladakh. Equipped with a large optical reflector of 21m diameter, the MACE telescope is the largest gamma-ray telescope in Asia and the second largest in the Northern Hemisphere after the LST-1 of the CTA observatory. An array of three MACE-like telescopes is being proposed at Hanle for stereoscopic observations of gamma-ray sources with better flux sensitivity and improved energy and angular resolutions. This, along with another proposed array of a new type of small-size Schwarzschild–Couder telescopes, will help in a wider energy coverage from tens of GeV to a few hundreds of TeV of the gamma-ray sky. The GRAPES-3, a particle array detector at Ooty in Tamilnadu, can probe the high energy phenomena in the energy range from a few TeV to tens of PeV in the Universe. A similar array of plastic scintillators and muon detectors will be installed soon at the MACE site in Hanle. Thus, the Hanle site in the Ladakh region may host several ground-based high-energy astronomy facilities in the future and will emerge as a world-class observatory in the country.

2.1 *Current observation facilities*

Ground-based high-energy gamma-ray astronomy is closely linked to the idea of exploring the Universe in the lowest wavelength region of the electromagnetic spectrum. It is concerned with the study of the sources of energetic non-thermal radiation in the Milky Way Galaxy and beyond, propagation of gamma-ray photons in the observable Universe, particle acceleration in cosmic environments, and other complementary astroparticle physics topics such as extragalactic background light, intergalactic magnetic field and signature of weakly interacting massive particles as dark matter candidate (Ong 1998; Holder 2012; Funk 2015; de Almeida & Doro 2022). The ground-based high energy astronomy in the GeV–TeV domain is strongly connected to the scientific investigations for the cosmic rays, the highest energy particles in the Universe. Detection of these energetic radiations using ground-based instruments is possible by measuring extensive air showers initiated by the high energy gamma-ray photons or the cosmic ray particles impinging onto the earth-atmosphere.

For the gamma-ray photons of energy range above 20 GeV, well-established techniques for the measurement of extensive air showers are based on the detection of Cherenkov light produced by the shower particles, observation of the fluorescence light emitted by air molecules which have been excited by the shower particles and the measurement of shower particles that reach the ground level. Instruments for measuring the Cherenkov light from an air shower are divided into Imaging Atmospheric Cherenkov Telescopes (IACTs) and Cherenkov Wavefront Sampling Telescopes (CWSTs). Ground-based gamma-ray observations using IACTs have been highly successful, with the discovery of more than 240 sources in the Universe over the last three decades. In India, two IACTs, namely TeV Atmospheric Cherenkov Telescope with Imaging Camera (TACTIC) and Major Atmospheric Cherenkov Experiments (MACE), are currently operational at Mount Abu, Rajasthan, and Hanle, Ladakh, respectively (Singh & Yadav 2021; Singh 2022). The TACTIC telescope, equipped with a 4m diameter light collector and 349-pixel imaging camera, belongs to the first generation of IACTs (Koul *et al.* 2007). It started

Figure 1. MACE telescope at Hanle, Ladakh.

its regular science observations in early 2000. It has significantly contributed to high-energy astronomy by monitoring TeV emissions from more than 15 potential gamma-ray sources in the last twenty years. The TACTIC telescope is being used for long-term monitoring of gamma-ray emission above 0.85 TeV from the selected active galactic nuclei. The current generation state-of-the-art MACE telescope (shown in Figure 1) has recently started its regular science observations (Yadav *et al.* 2022). Commissioning of the telescope took place in September 2021 after its first successful light on the night of 1 April 2021. Equipped with a 21m diameter quasi-parabolic optical reflector and 1088-pixel photomultiplier tube-based imaging camera, MACE can explore the deep gamma-ray Universe at high redshift in the energy range above 20 GeV with an excellent sensitivity of point source detection (Borwankar *et al.* 2020; Tolamatti *et al.* 2022). Currently, the MACE telescope primarily observes the crab nebula and blazars. Apart from the IACTs, a CWST named High Altitude GAmma Ray (HAGAR) has been operational since September 2008 at Hanle (Chitnis 2018). It is an array of seven Cherenkov telescopes, with each one of them consisting of seven para-axially mounted parabolic mirrors of 0.9m diameter each and UV-sensitive photomultiplier tubes mounted at the focus of each mirror to record the arrival time of Cherenkov shower front and Cherenkov photon density at various locations. HAGAR has successfully detected very high energy gamma-ray emission from a few active galactic nuclei above an energy threshold of 200 GeV (Saha *et al.* 2013).

The cosmic rays in the energy range above 10^{14} eV are investigated by the ground-based extensive air shower particle detector arrays. In this scenario, the Gamma Ray Astronomy PeV EnergieS phase-3 (GRAPES-3) is a major high-altitude, near-equator astroparticle physics facility, operated by the Tata Institute of Fundamental Research in Ooty, Tamil Nadu (Tanaka *et al.* 2012; Hariharan *et al.* 2020). It has been running 24 × 7 since 2000 with an array of 400 plastic scintillator detectors spread over 25,000 m^2 and a 560 m^2 area large muon telescope (world's largest muon telescope) to sample the electromagnetic and muonic components of cosmic ray air showers respectively. It allows us to study high-energy astroparticle phenomena from 1 TeV to 10 PeV energy range, including the measurements of cosmic ray energy spectrum and composition while providing an overlap with various direct measurements in space, small and large scale cosmic ray anisotropy and multi-TeV gamma-ray source searches from a near-equatorial location. In addition, the muon telescope is designed to record muon flux above 1 GeV energy from 169 directions covering 2.3 sr sky at a rate of 3 million muons per minute, thus providing high statistical measurements of the cosmic ray modulation induced by solar and atmospheric phenomena on minute time scales. The physics domains that are currently being probed with the GRAPES-3 experiment are measurement of cosmic ray energy spectrum and composition over 10 TeV–10 PeV, measurement of small and large scale cosmic ray anisotropy, and search for multi-TeV point and diffuse gamma-ray sources in TeV–PeV energy domain. In the GeV energy domain, solar and heliospheric phenomena, space weather and its prediction, monitoring the upper atmospheric temperature, and particle acceleration in thundercloud electric fields are among the key objectives of the GRAPES-3 observatory.

The limited sensitivity of Cherenkov telescopes such as TACTIC and MACE can be complemented by the large area extensive air shower arrays, which provide a wide field of view and nearly 100% duty cycle extending observation far beyond TeV. The GRAPES-3 air shower array is ideally suited for gamma-ray studies in the TeV–PeV range. Due to its near-equatorial location, it can view the galactic center. The ongoing expansion of the GRAPES-3 muon telescope should permit the determination of the ratio of gamma rays to protons to an unprecedented precision of 1 part in 10^5. This should enable the identification of multi-TeV gamma-ray emissions from extended sources. Expanding the scintillator array with a denser configuration around the muon detector would bring down the energy threshold to TeV energy, providing overlapping observations with Cherenkov telescopes.

2.2 *Next-generation observation facilities – World vision*

In the field of very high energy gamma-ray astronomy, the Cherenkov Telescope Array (CTA) is the next-generation ground-based multi-national observatory comprising 50–100 IACTs located in the northern (La Palma in Spain) and southern (Paranal in Chile) hemispheres each (Acharya *et al.* 2013). Expected to be operational in 2025, CTA will be the world's largest and most sensitive high-energy gamma-ray observatory. The observatory will comprise IACTs of three classes: (i) 4 Large Size Telescopes with 23m diameter each (sensitive to gamma rays with energy below 200 GeV), (ii) 25 Medium Size Telescopes of 12m diameter each (for the energy range between 100 GeV and 10 TeV) and (iii) 70 Small Size Telescopes with 3–5m diameter each (up to 300 TeV) for southern site only. This array of different telescopes will improve the sensitivity and energy coverage from a few tens of GeV to beyond 300 TeV and the angular resolution by at least an order of magnitude compared to the existing facilities. The expected lifetime of the CTA observatory is 35 years.

Two dozen collaborations operate extensive air shower arrays worldwide, in the USA, Europe, Japan, China, Australia, South America, and Antarctica. However, only a handful can be compared with GRAPES-3 regarding physics potential or versatility. These include KASCADE-Grande Germany operated by European groups, Tibet-AS$_\gamma$ operated by Japanese and Chinese groups, and ARGO-YBJ by Italian and Chinese groups. These Tibet-based groups have merged to form the Large High Altitude Air Shower Observatory (LHAASO) based in western China. GAMMA is a collaboration of Armenian, Russian, and European groups. There are also experiments conducted at high altitudes in the Pamir and Chacaltaya mountains by Russian, Japanese, and South American scientists. Due to a dense array of scintillators and a large-area muon-telescope, a relatively high-altitude GRAPES-3 array offers several advantages relative to other arrays in sensitivity for composition and episodic phenomena. A near-equator location provides unprecedented views of both northern and southern skies, including the galactic center. Longitude differences of 5 and 10 h relative to Europe and the USA allow monitoring of transient sources when they cannot be viewed by instruments in Europe and the Americas. This makes GRAPES-3 a valuable part of the international scene, with the potential to contribute to multi-messenger studies in astrophysics.

2.3 *Upcoming facilities in India*

Equipped with the experience gained from the TACTIC and MACE telescopes, the following experimental facilities are proposed for ground-based high-energy astronomy in the country:

- Stereoscopic MACE System (SMS) at Hanle: An array of three MACE-like IACTs for observation of gamma-ray sources in stereoscopic mode to achieve a better point source flux sensitivity and improved energy and angular resolutions in the energy range above 20 GeV.
- Schwarzschild–Couder Telescope Array (STA) at Hanle: An array of 4m class dual mirror telescopes for a wide field of view and extended energy coverage up to 100 TeV.
- An array of plastic scintillators and muon detectors (similar to the GRAPES-3) at Hanle: An experiment for TeV to PeV Gamma-Ray Astronomy and Cosmic Ray Research.

2.4 *Developments over the next 3 years*

- Science operation of the MACE telescope to study different high-energy gamma-ray sources.
- Development and Installation of Silicon Photomultipliers based 256-pixel imaging camera at the TACTIC telescope.
- Simulation study for the Stereoscopic MACE System at Hanle.
- Simulation study for the 4m class Schwarzschild–Couder Cherenkov Telescope (SCT) at Hanle.
- Expansion of the GRAPES-3 experiment by doubling areas of the scintillator array and muon-telescope.
- Feasibility studies for deploying a phased radio antenna array for cosmic ray measurements over 10^{16}–10^{19} eV energies at the GRAPES-3 experiment.
- Development and Installation of a SiPM camera-based Imaging Atmospheric Cherenkov Telescope at the GRAPES-3 experiment.

2.5 *Facilities over the 3–7 years*

- Development and Installation of Stereoscopic MACE System at Hanle.
- Installation of TACTIC-like telescope with 256-pixel Silicon Photomultipliers based camera at Hanle.
- Development and Installation of an array of ten 4m class Schwarzschild–Couder Cherenkov Telescope at Hanle.
- Development of GOALS site at Mount Abu as a base laboratory for high-energy gamma-ray astronomy instrumentation.
- Establishing a multi-messenger observation network for gamma-ray astronomy in India.

2.6 *Vision for the next 10 years*

The MACE telescope at Hanle has become a unique experimental facility for carrying out front-line research to explore the mysteries of high energy Universe. Integrating the proposed Stereoscopic MACE System with the Schwarzschild–Couder Telescope Array (STA) will provide near-simultaneous gamma-ray observations over a wide energy range from 20 GeV to 100 TeV. Such large-scale developments will be powerful drivers of innovative technologies for extracting maximum information from weak signals. Efforts in the fields of machine learning, artificial intelligence, data mining, advanced statistics, software development, and curation will help in developing high-level expertise within the country. Vigorous outreach programs will be initiated to help captivate young talents to join the high-energy astrophysics research and inspire everyone in general. Apart from the academic and scientific enrichment of Indian researchers and young minds, the activities associated with ground-based high-energy astronomy will also lead to the creation of job opportunities for the local population in Ladakh. In addition to scientific research, steps to develop and showcase astro-tourism in the high-altitude Himalayan desert in the Ladakh region will be initiated. This can bring new opportunities for sustainable socio-economic development and educate the country's citizens in astronomy and astrophysics.

To compete with the international experiments in the sub-PeV gamma-ray domain, it is proposed that the GRAPES-3 array be enhanced several times. Especially the muon detector, which is a key instrument for charged cosmic ray background rejection, needs to be expanded several times along with the expansion of the scintillator array. The Knee to Ankle region in the cosmic ray spectrum is believed to be the energy range in which the cosmic rays originating in sources within the Galaxy give way to cosmic rays of extra-galactic origin, and there is a great interest in this region in the wider cosmic ray community. The radio measurements, together with the GRAPES-3 measurements, could cover an energy range from 10^{13} to 10^{19} eV while providing an overlap with space-based measurements below 10^{14} eV and covering a Galactic to extra-galactic transition region from the Knee to the Ankle region.

A strong focus on the Indigenous development of cutting-edge instrumentation and nurturing of young talent has been the hallmark of the GRAPES-3 team. It will continue to form the basis of our future endeavors. The GRAPES-3 facility will provide an excellent platform for multi-disciplinary collaboration across universities and institutions and the training of talented young scientists and engineers in experimental areas in India.

3. High-energy space-based astronomy facilities

AstroSat has set a benchmark as the space-based astronomical observational facility for the Indian high-energy astrophysics community. Historically, the observational high-energy astrophysics community, or the X-ray/soft gamma-ray astronomy community, had been concentrated in the few research institutes where instrument development was possible for the balloon-born or space-borne observations essential in this field. However, with the advent of data archives and easy access to data from international X-ray observatories in the early 21st century, the observational X-ray astronomy community in India started decoupling from the experimental X-ray astronomy community. Today, with the availability of an internationally competitive facility like AstroSat, and thanks to the sustained efforts by the AstroSat Science Support Center, the observational X-ray astronomy community in India has now grown significantly. It is now spread to many universities and colleges across the entire length and breadth of the country. A particularly noteworthy aspect here is that many young astronomers have started their research careers using observations from AstroSat and have a long way to go before they can contribute to the field's growth in the country. Unfortunately, the Indian experimental X-ray astronomy community has not grown commensurately, and there is an urgent need to support and strengthen the existing experimental groups. A definitive way to achieve this is to quickly identify and execute new programs while carefully considering the dilemma between a 'niche' and internationally competitive facility vs. a 'general purpose' but possibly not the world best facility. Thus, the overall X-ray astronomy community in India must have a long-term vision and clear path over the next few decades, which can cater to the aspirations of both the observational and experimental communities. The following sections outline such a vision, arrived after broad consultation with several stakeholders, for the space-borne observational facilities catering to the high-energy astrophysics community in India.

3.1 *Next-generation observation facilities – World vision*

Observational high-energy astrophysics using space-borne facilities is a highly active and growing field internationally, with many groups involved in using the present facilities and developing future facilities. Many operational missions provide observations in the X-ray and gamma-ray bands, and many missions are coming up in the future, as listed below.

Ongoing major high-energy space missions:

- *Chandra and XMM-Newton* Though launched more than two decades ago, both observatories are still going strong and provide the most sensitive observations in the classical X-ray energy range of 1–10 keV.
- *NuSTAR* This observatory has spent over a decade in space as it was launched in June 2012 by NASA. This is the only X-ray mission in space providing sensitive observations beyond 10 keV with a focusing rigid X-ray telescope.
- *AstroSat* launched in September 2015, it is the first Indian space mission dedicated to Astronomy. The instruments cover the energy bands and 0.3–100 keV and Near and Far Ultraviolet bands, enabling the simultaneous multi-wavelength observations of various astronomical objects with a single satellite.
- *Insight-HXMT* launched in 2017 provides observations up to $\sim$250 keV, though with moderate sensitivity using collimated instruments over the entire energy range of 1–250 keV.
- *NICER* was launched on 3 June 2017, and it is on an International Space Station (ISS) payload designed to study neutron stars at soft X-ray energy range (0.2–12 keV).
- *IXPE* launched in December 2021 is the first dedicated mission for X-ray polarization measurement and is revolutionizing the field of X-ray polarimetry.
- *MAXI* launched in 2009 is an all-sky monitor onboard the International Space Station providing long-term monitoring of the highly variable X-ray sky.
- *Swift* launched in 2004 is the dedicated mission to observe transient sources, with the BAT instrument providing detection and XRT providing quick follow-up observation of fast transients like GRBs. BAT also provides long-term monitoring of hard X-ray sky.
- *Fermi* This unique observatory brings together the astrophysics and particle physics communities and was launched on 11 June 2008. It provides observations up to 300 GeV covering very high energies.
- *Integral* observatory was launched in October 2002 aboard Russian rocket and provides imaging and spectroscopic data in the energy range of 15 keV to 10 MeV.

Upcoming major high-energy missions:

- *XRISM* This X-ray observatory will use state-of-the-art micro-calorimeter technology to measure X-ray photon energies with ultra-precision, focusing X-ray optics and a CCD camera. It will be a joint venture between JAXA (Japanese Space Agency), NASA, and ESA. The expected launch date is 2023 for the observatory.
- *eXTP* The enhanced X-ray Timing and Polarimetry mission (eXTP) is a science mission designed to study the state of matter under extreme conditions of density, gravity, and magnetism. It uses a combination of instruments to enable, for the first time, simultaneous spectral-timing-polarimetry studies of cosmic sources in the energy range from 0.5 to 30 keV. The planned launch date of the mission is 2027.
- *SVOM* The Space Variable Objects Monitor (SVOM) will be a small X-ray astronomy mission led by the Chinese National Space Administration (CNSA; China) and the National Center for Space Studies (CNES; France). It is planned for a three-year mission with a launch data in 2023. This observatory will employ several instruments, including wide field detectors, which can trigger on unknown sources (like GRB) and rapidly slew to bring other narrow field instruments on the source and send alert notices for coordinated observations with other observatories. Thus, its primary goal is to provide rapid localization with high accuracy.
- *COSI* The Compton Spectrometer and Imager (COSI), a NASA-selected mission, is a wide-FOV telescope designed to survey the gamma-ray sky at 0.2–5 MeV energies, performing high-resolution spectroscopy, imaging, and polarization measurements. It will employ germanium cross-strip detectors to enable the study of 0.511 MeV emission from antimatter annihilation in the Galaxy, mapping radioactive elements from nucleosynthesis, determining emission mechanisms and source geometries with polarization, and detecting and localizing multi-messenger sources.

- *Athena* This is the X-ray observatory mission selected by ESA, within its Cosmic Vision program, to address the Hot and Energetic Universe scientific theme. It is the second L(large)-class mission within that program and is due for launch in the early 2030s.

3.2 *Upcoming developments in India*

3.2.1 X-ray imaging The telescopes in the X-ray/soft gamma-ray band can be divided into two categories depending upon their configuration for collecting the photons. Direct-view telescopes are mainly detectors that are provided with collimators or indirect imaging methods such as coded masks. The focusing telescopes are the ones employing focusing optics. The latter category of telescopes concentrates the collected photons on the focal plane, where the detectors are placed. Since the photon collecting area and the detector area/volume are decoupled in the focusing telescopes, they typically have greater sensitivity than the direct view telescopes. The most important advantage of X-ray-focusing telescopes is that they allow accurate X-ray imaging. X-ray imaging spectroscopy is an important and necessary advancement in several areas of Astronomy, Solar physics, and planetary science.

After the development of the Soft X-ray Telescope for AstroSat, there has not been significant progress in the development of X-ray mirrors in India. Extending the energy range of the X-ray optics beyond 10 keV requires multilayer X-ray mirrors. Such mirrors of a few cm in size with bilayers ranging from 50 to 300 were developed at RRCAT, characterized, and successfully tested for use in space. Some of these mirrors with a Si substrate were also back-thinned to yield ultra-thin mirrors. However, a sustained X-ray mirror fabrication program that would cater to space science missions is in a nascent stage in India. A large team with stakeholders must plan, participate, and take forward such programs requiring long-term commitment. Efforts have been initiated recently to fabricate X-ray mirrors using slumped glass. Full shell mirrors using the Electro Nickel Replication technique are also being explored. The goals of this program are development, characterization, assembly, and technology transfer to other industries.

Developing X-ray optics that can focus X-rays beyond 10 keV is highly challenging. Hence, today, there is only one operational hard X-ray telescope mission, NuSTAR, which can focus X-rays up to $\sim$80 keV. Also, no other approved mission will have a hard X-ray telescope over the next decade. Thus, this area presents an excellent opportunity for the Indian community to have an internationally competitive X-ray mission.

3.2.2 Collimated large area detectors While focusing on X-ray optics leads to much higher sensitivity, the total effective area is usually limited in such telescopes due to the technical difficulties in realizing very large area optics. Hence, the collimated detectors, which can be configured to have a collecting area of a few square meters, are still relevant for science cases such as timing studies of bright X-ray sources, which require many X-ray photons. This area is significant for the Indian X-ray community, whose traditional strength is in the timing and spectroscopic analysis of bright galactic X-ray sources. Hence, it is important to keep an option open for such a mission in the near future.

3.2.3 Soft X-ray polarimetry X-ray polarimetry is at an early stage of exploration in the present epoch. Polarization studies of various X-ray sources will help answer many outstanding questions in X-ray astronomy. X-ray polarimetry in the soft energy band of 2 to 8 keV has been made possible with IXPE, and many X-ray sources are observed with imaging. A soft X-ray polarimeter is essential to continue studies of these X-ray sources with better sensitivity in the soft X-ray energy band of 2 to 8 keV for a better understanding of the accretion physics and geometry in these systems. A GEM-based soft X-ray polarimeter with suitable optics will help achieve this objective. Polarization measurements in this energy range play a crucial role in studying the physics behind the emission mechanism and accretion geometry, especially tied with the accretion discs close to compact objects where extreme gravity and magnetism manifest in different ways with radiation from jets, accretion discs, varying profiles of reflection features due to extreme gravity, pulse profile variations due to extreme magnetism, etc. X-ray polarization studies in this soft X-ray energy band are of prime importance, with many niche science prospects to be explored.

3.2.4 Hard X-ray polarimetry Polarization measurements at X-ray energies have been sought after over the past five decades. However, real progress in this direction has been possible only for the past year after the launch of the IXPE mission, which provides sensitive X-ray polarization measurements in the energy range of 2–8 keV. The upcoming XPoSat mission will aptly complement IXPE and provide polarization measurements in the energy range of 8–30 keV. The CZTI instrument onboard AstroSat has rudimentary polarimetric capability in the energy range of 100–380 keV for very bright X-ray sources. However, the intervening energy range of 30–100 keV is not covered by any present or approved future mission and thus presents a niche opportunity for the Indian X-ray community. The polarization measurements in this energy range are important because the physical processes responsible for emission in this energy range are typically different than those at the soft X-ray energies.

3.2.5 All sky monitoring X-ray sources are known for variability. The high-energy sky is intrinsically variable, with transient sources appearing, varying, and disappearing over the timescales of a few minutes to a few months. Different classes of objects have different timescales of variability that link to the geometry of emission and the other physical processes underlying the emission mechanisms. The time-resolved spectral study of X-ray binaries plays a key role in understanding the dynamics of accretion physics and geometry of accretion in these sources. It is crucial to study the spectro-temporal behavior of the sources over longer timescales, like a year or more, in addition to having possible continuous monitoring of the sources with minimal time gaps. A Wide-Field Imaging Soft X-ray Spectrometer with a wide FoV will provide an excellent platform to carry out long-term spectro-temporal study of astrophysical sources.

Based on the above considerations, the vision for high-energy space-based observational facilities is outlined in the following sections.

3.3 *Developments over the next 3 years*

The only approved X-ray astronomy mission is XPoSat, which will be operational over the next three years.

3.3.1 XPoSat XPoSat will be the second dedicated astronomical X-ray polarimeter mission in space after the IXPE mission of NASA launched in December 2021. It covers a complementary energy band of 8–30 keV compared to the 2–8 keV band covered by IXPE. POLIX onboard XPoSat will play an important role in the emerging field of X-ray polarimetry of high-energy astrophysical sources. POLIX utilizes Thomson scattering of X-ray photons to study polarization in astronomical sources at the X-ray band. POLIX employs a collimator, a Be scatterer, and four position-sensitive proportional counter detectors placed around the scatterer. The collimator restricts the field-of-view to a small part of the sky, $3^\circ \times 3^\circ$.

The POLIX instrument, working in the 8–30 keV band, will be very useful for the measurement of the degree and direction of the X-ray polarization of a few bright cosmic X-ray sources, including accretion-powered binary X-ray pulsars, galactic black hole candidates, rotation-powered pulsars and magnetars, supernova remnants and pulsar wind nebulae, and active galactic nuclei. XPoSat will also carry a spectroscopic payload, XSPECT, that will provide simultaneous X-ray spectroscopic data in the 0.8–15 keV energy range and polarization measurements.

3.4 *Facilities over the 3–7 years*

This time frame presents ‘a great possibility’, as many of the mission concepts being discussed currently are likely to see the light during this time frame. Particularly noteworthy concepts are briefly described below, and at least one, possibly more (ideally all) of them are expected to be realized.

3.4.1 Daksha Daksha is a proposed mission for broadband high-energy all-sky coverage, and the mission is dedicated to X-ray and gamma-ray transient astronomy. The main scientific objective of this mission is to detect and localize the electromagnetic counterparts of the gravitational wave sources, which are expected to be detected as faint short GRBs. The mission comprises two satellites launched in a near-equatorial low-earth orbit (LEO) to mitigate the impact of the South Atlantic Anomaly (SAA) and earth occultation to cover the entire sky for GRB detection continuously. It will cover an energy range from $\sim$1 keV to $\sim$1 MeV using multiple units of three types of X-ray detectors.

3.4.2 Collimated hard X-ray polarimeter This mission concept aims to exploit the niche area of hard X-ray polarization measurement in the 20–200 keV energy range, which is not planned by any other mission over the next decade. It will consist of a large array of Compton X-ray polarimeters. The individual Compton X-ray polarimeter is an evolution of the focal plane Compton X-ray polarimeter (CXPOL) developed as a focal plane instrument for the hard X-ray telescope. It has a large collecting area for its scatterer. The proposed configuration for this mission can provide sensitive hard X-ray polarization measurements for many galactic X-ray sources brighter than 50 mCrab.

3.4.3 Large area timing-spectroscopy mission This mission concept aims to continue the legacy of AstroSat by providing X-ray timing and spectroscopic observations of bright X-ray sources. It can be realized as a large array of collimated X-ray detectors, large area SCD or SDD similar to those used in eXTP, or as an array of X-ray concentrators coupled with small SDD modules, similar to those used in NICER. Similar modules of the XSPECT (fewer in number) will be flown onboard XpoSat. Hence, realizing the mission on a realistic time scale of 3–7 years is possible.

3.4.4 Soft X-ray polarimeter with concentrator optics The primary objective of this instrument is to carry out polarization measurements in the soft X-ray energy band similar to that of IXPE but aimed at having better sensitivity at the higher end of the energy band and additional observations of many more X-ray sources to add to the observations carried out by IXPE. This instrument is a GEM-based soft X-ray polarimeter with TPC (time-projection chamber) for readout that works in the 2–10 keV energy range. The instrument would require an X-ray optics that works like a concentrator to enhance the overall sensitivity. The X-ray concentrator shall include truncated paraboloid shells arranged in a nested configuration to achieve a con-focal system of paraboloids. The detector shall be placed at the focal plane of the concentrator shells. An improvement upon the presented configuration can be achieved by optimizing the coatings on the mirror shell.

3.4.5 Wide field X-ray imaging spectrometer All sky monitors with a wide field of view are essential to tracking the transient events in the X-ray sky, which helps detailed studies of various sources to understand the physics behind such transient phenomena in these sources. The wide field-of-view, along with good angular resolution and much better sensitivity for simultaneous spectro-temporal studies of all the sources observed within the FoV of the instrument in a particular stare, is possible with novel state-of-art lightweight optics like micro pore optics in lobster eye configuration. The configuration for a wide-field X-ray Imaging Spectrometer includes CMOS detectors with lobster eye optics similar to the one proposed for the Theseus mission by ESA. A similar configuration has been demonstrated in one of the recent X-ray instruments flown by China, the Lobster Eye Imager for Astronomy (LEIA), launched in July 2022. Such a wide-field X-ray spectrometer will also aid in capturing the sources in outbursts for more detailed follow-up observations by other observatories in other wavebands.

3.4.6 Other possibilities Some groups are contemplating a few other mission concepts and might be realized if these can achieve enough community support and technological readiness. One such concept is a small-scale joint UV X-ray spectroscopy dedicated to long-term transient studies. It aims to densely follow the outbursts of most of the transient sources with simultaneous UV and X-ray spectroscopic observations. Another concept is for a space-borne high-energy gamma-ray and cosmic ray detector to cater to the astroparticle physics community. A third concept being deliberated is for imaging soft X-ray spectroscopy of the Sun with moderate spatial resolution but a high time cadence. Such observations can be beneficial for studying the quiescent regions of the Sun in the presence of bright, active regions or flares.

3.5 *Vision for the next 10 years*

3.5.1 Broad-band X-ray telescope mission X-ray polarimetry of celestial sources is unexplored mainly, though there have been many theoretical predictions of the expected polarization from different classes of X-ray sources. Spectroscopic and timing observations with higher sensitivity and largely unexplored measurement of polarization at energies up to about 100 keV are essential to solve various open problems and vastly improve the understanding of the physics of emission in X-ray sources. This is a niche area where the Indian X-ray astronomy community could impact the global scenario.

Amongst the past X-ray instruments, most of the sensitive ones have been in the soft X-ray regime ($<$10 keV), owing to the use of focusing X-ray telescopes operating in that energy range. On the other hand, the hard X-ray band is scientifically very important in studying non-thermal physical processes. Sensitive observations in this band can address many critical issues in X-ray astronomy, where our present understanding is severely limited.

'Broad Band X-ray Spectro-Polarimetry Mission' is the only mission to address the broadband X-ray spectro-polarimetric characteristics of X-ray sources in the foreseeable future. The Broad Band X-ray Spectro-Polarimetry Mission will be unique and a leading astronomy mission in its time frame.

3.5.2 Technology development Micro-calorimeter Ultra high energy resolution spectroscopy with an energy resolution better than 5 eV (@5.9 keV) will be a major thrust area in X-ray astronomy with upcoming missions such as XRISM and Athena. Many other mission concepts currently under study are also planned around such capability. However, the Indian X-ray community has not yet adequately been exposed to this area in terms of observational, interpretation, and experimental capability. While the observational capability is likely to get developed with exposure to international missions once these are operational, it is also important to initiate the development of some experimental capability in this field so that the Indian X-ray community can plan for a mission having ultra-high energy resolution spectroscopy later.

Focusing at soft gamma-ray energies The traditional X-ray focusing is realized using reflective X-ray mirrors that reflect the incident X-rays at grazing angles. This method is limited to focusing X-rays at energies $\sim$100 keV, even after employing multi-layer coated X-ray mirrors such as those used in the NuSTAR mission. The lack of focusing capability at higher energies results in significantly lower sensitivity. Hence, it is highly desirable to achieve X-ray focusing at energies beyond $\sim$100 keV, and one possibility is to employ X-ray diffraction optics for this purpose. In principle, this can be achieved by arranging appropriate X-ray diffracting crystals in a configuration known as a Laue lens. It is an up-and-coming method, and if the necessary technology is developed shortly, a mission can be planned at a later stage, which would be the first of its kind in the world.

Formation flying Because of the grazing incidence requirement of the X-ray optics, the X-ray telescopes typically have considerable focal lengths. The present generation X-ray telescopes have focal lengths up to $\sim$10 m. However, for the next generation X-ray telescopes having an order of magnitude larger effective, it would be essential to have a longer focal to $\sim$50 m or more to maintain the same grazing incidence angle – length to increase the overall effective area of the telescope. Similar or larger distances are involved in the mission configurations considering X-ray interferometry or soft γ-ray focusing. Long focal lengths are typically achieved using extendable booms. However, maintaining such large distances with required stability and point accuracy is extremely difficult with booms. In such cases, the alternative possibility is to deploy two independent spacecraft housing X-ray optics and detectors and maintain their relative position within the required accuracy. Such configuration is known as formation flying and has been employed, e.g., in the LISA Pathfinder experiment. It would be important to develop such technology for the Indian spacecraft so that the next generation of Indian X-ray missions, and many other space-borne experiments requiring formation flying, can be planned.

3.5.3 *Recommendations*

- Revival and augmentation of the X-ray beam facility at Hyderabad for calibration of X-ray payloads.
- Multilayer mirror fabrication for hard X-ray imaging.
- Identification of industry partners for the production of X-ray mirrors.
- Development of new focal plane detectors for imaging (e.g., X-ray CMOS).

X-ray beamline facility at the Hyderabad Future Indian X-ray Astronomy payloads need competing sensitivity; hence, X-ray optics is necessary. While X-ray optics is being developed, ground testing facilities are essential to characterize the optics and the integrated telescope system. SXT, the first X-ray imaging satellite in India on AstroSat led by TIFR, had developed a beamline for testing the SXT payloads, which will be an asset to future development with required upgradation. To understand and develop the required augmentation, the following is required to be carried out: (a) the current capability of the facility (in terms of size, energy range, etc.), (b) identify the augmentation requirement keeping in mind the future development, and (c) generate a proposal for the same along with the resource required and timeline. A team of experts will visit the facility to assess the current capabilities and discuss with the national X-ray astronomers (through a brainstorming session) to gather future requirements before arriving at a proposal for the augmentation.

Dedicated beamline at a synchrotron source Dedicated synchrotron beamline at RRACT either in Indus-2 or the proposed HBSRS, primarily for polarimetric calibration, but can also be used as a general-purpose X-ray beamline.

4. UV-optical observation facilities

4.1 *Next generation observation facilities – World vision*

It is generally recognized that the visible band, though quite narrow, is particularly richly endowed with diagnostics of physical conditions. It is, therefore, not surprising that objects discovered in other electromagnetic regions need to be observed in optical to establish their identity. On the other hand, the UV region is extraordinarily rich in spectroscopic diagnostics of the plasma found in a wide variety of astronomical objects and environments. Therefore, observational capability in the UV and visible spectral regions is crucial in studying topics ranging from planetary systems to galaxy formation.

The world has witnessed some unprecedented images from the recently launched James Webb Space Telescope (JWST), and it has also started providing some exciting new results, such as the discovery of Earth-like terrestrial exoplanet LHS475b.[2] While the JWST is expected to make the bulk of discoveries in this decade, at the same time, three new extremely large telescopes (ELTs) are being built that will be operational in the next decade to further our understanding on the birth and growth of the Universe. They are the Thirty Meter Telescope (TMT-30-m primary), the European Extremely Large Telescope (EELT-39-m primary), and the Giant Magellan Telescope (GMT-25-m primary). These ELTs will study some of the earliest objects, shed light on the physics of the early Universe, and help astrophysicists better understand dark matter.

The international community in the past two decades has been quite successful in conducting modern UV-optical and near-IR wide-field imaging surveys such as GALEX (Bianchi & GALEX Team 1999), SDSS (York *et al.* 2000), Pan-STARRS (Chambers & Pan-STARRS Team 2016), the Hyper Suprime-Cam Subaru Strategic Program (Aihara *et al.* 2018), the Dark Energy Survey (Dark Energy Survey Collaboration 2016), Gaia (Gaia Collaboration 2016) and 2MASS (Kleinmann 1992) which paved the way for significant advancements in our understanding of the Universe. However, to realize the full scientific potential of these imaging surveys, many (if not all) of the sources identified in these surveys must be studied spectroscopically. The Sloan Digital Sky Survey (SDSS) has conclusively demonstrated the scientific power of the combination of wide-field imaging and spectroscopic surveys. The Large Synoptic Survey Telescope (LSST) is set to establish a new benchmark by undertaking a 10-year-long imaging survey of the southern sky in six optical filters with an unprecedented combination of area, depth, and cadence.

Wide-field spectroscopic survey is critical in addressing scientific issues related to most astrophysical topics such as stellar populations, Milky Way structure, the evolution of galaxies and AGN, the physics of dark matter and dark energy, and the signatures of inflation from the early universe. The data thus generated will help constrain the sources' nature, radial velocity/redshift, internal stellar and gas dynamics, chemical composition, thermodynamic conditions, and line-of-sight radiative geometry. Consequently, several efforts have been initiated worldwide to develop highly multiplexed, wide-field optical multi-object spectroscopic capability on 4–10-m class telescopes to conduct spectroscopic follow-up observations of the sources that will be identified in future surveys like LSST and from space like Euclid and WFIRST (see Figures 2 and 3). Note that India will not be included in these upcoming surveys.

[2]https://www.nasa.gov/content/james-webb-space-telescope-latest-news.

4.2 *Existing UV and optical facilities*

India has several small and medium size (SMFs) facilities operational at $\sim$0.35–5 μm wavelength range. The SMFs are facilities that have primary mirror aperture sizes ranging from 1 to 4 m. India hosts several such ground-based telescopes (Figure 4; operating institute, location, and year of commissioning are given in parenthesis), which form the work-horse facilities for Indian astronomers. These telescopes are equipped with imagers, polarimeters, and low-, medium- and high-resolution slit spectrographs. India's lone space observatory, AstroSat, has been functional since 2015, with payloads covering the energy bands of Ultraviolet (Near- and Far-UV) and a limited optical and X-ray regime (0.3–100 keV). Besides the HST, the ultraviolet Imaging telescope (UVIT) onboard AstroSat is presently the only operational facility in the UV worldwide.

It is apparent in Figure 5 that globally, the astronomical community has shifted its focus from smaller aperture telescopes to bigger (>3-m) ones. In India, SMFs offer a total collecting area of 30 sq.m, but they may require an audit to determine operational efficiency. Atmospheric/sky conditions of these telescope sites may be one of the major obstacles; however, the management aspects of these telescopes, too, require an audit. For instance, various institutions manage these telescopes and allocate observing time through different time allocation committees (TACs), which may result in duplication and low scientific outputs. A single TAC managing time allocation for all the SMFs would be more pragmatic in optimizing their use for a higher scientific impact and cost-effectiveness. It also helps in managing back-end instruments more efficiently and enhances competitiveness.

India's efforts to install a 10-m class telescope on a high-altitude dry site began in 1984. However, even after

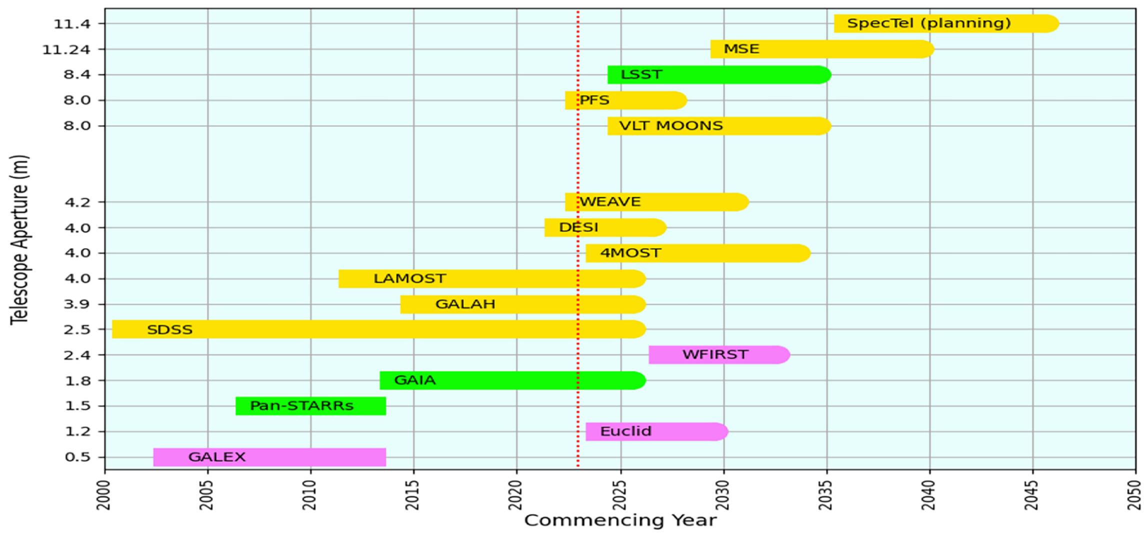

Figure 2. Aperture size and the year of commencing of ground-based surveys in both imaging (green) and spectroscopic (cyber-yellow) modes. The surveys from space are depicted in magenta. The year 2023 is marked with a dotted line.

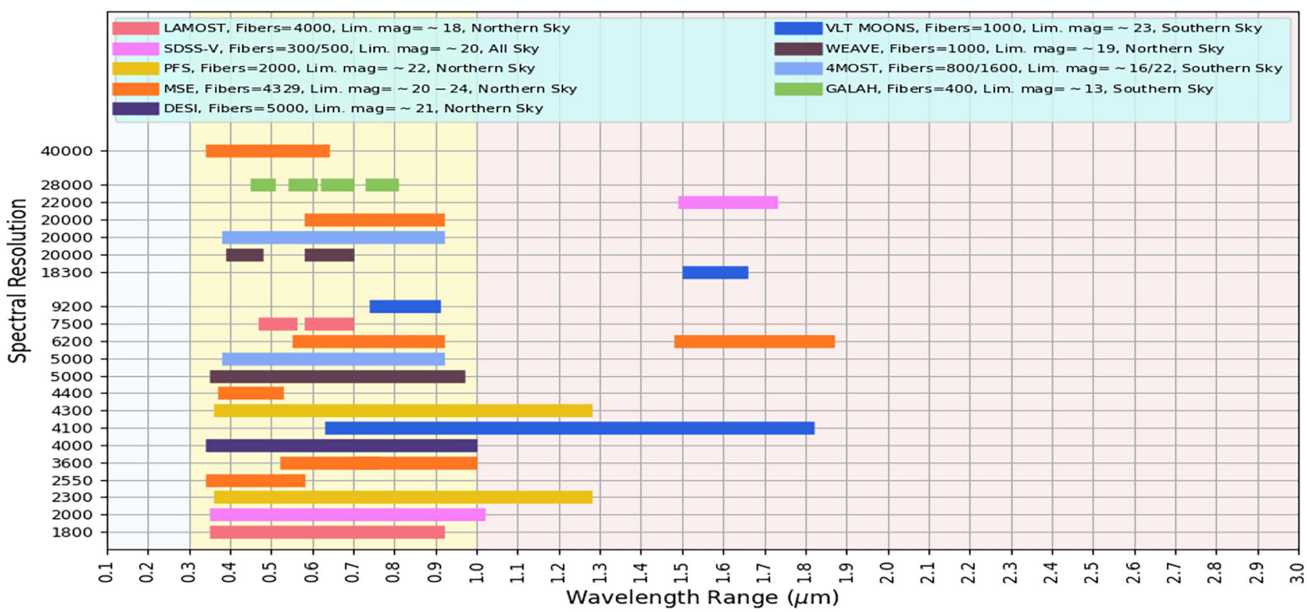

Figure 3. Spectral resolution and wavelength range of some of the ongoing and future spectroscopic surveys. The limiting magnitude of the survey, sky coverage, number of fibers used in the fiber-fed spectrograph, etc., are listed in the figure. Note that India is not part of any of the above upcoming survey programs. Collaboration with MSE would be beneficial if the project obtains formal approval. Survey specifications are from Yan *et al.* (2022) and McConnachie *et al.* (2016).

close to four decades, we still do not have a 10-m class telescope despite making several attempts. The initial proposal was to install a 6.5-m telescope in the 1990s. The recommendation then was to install a smaller aperture (2-m) telescope and demonstrate the capability to successfully run it in the remote and hostile environment of the Leh/Ladakh region, which was then identified as one of the best sites in the trans-Himalayan region at an altitude of $\gtrsim$4000 m to develop facilities for optical and infrared astronomy (HIROT Team 1996). Following the commissioning of the Himalayan Chandra Telescope (HCT) at Hanle in 2000, a proposal to install a 10-m class telescope was initiated in 2006, a period when 10-m class telescopes were getting installed elsewhere in the world (see Figure 5) However, even after more than two decades of the successful operation of the HCT at Hanle, we still lack a 10-m class telescope.

Presently, with our participation in the TMT, some of the participating Indian institutes and Indian industries are in a better position to take up the challenge

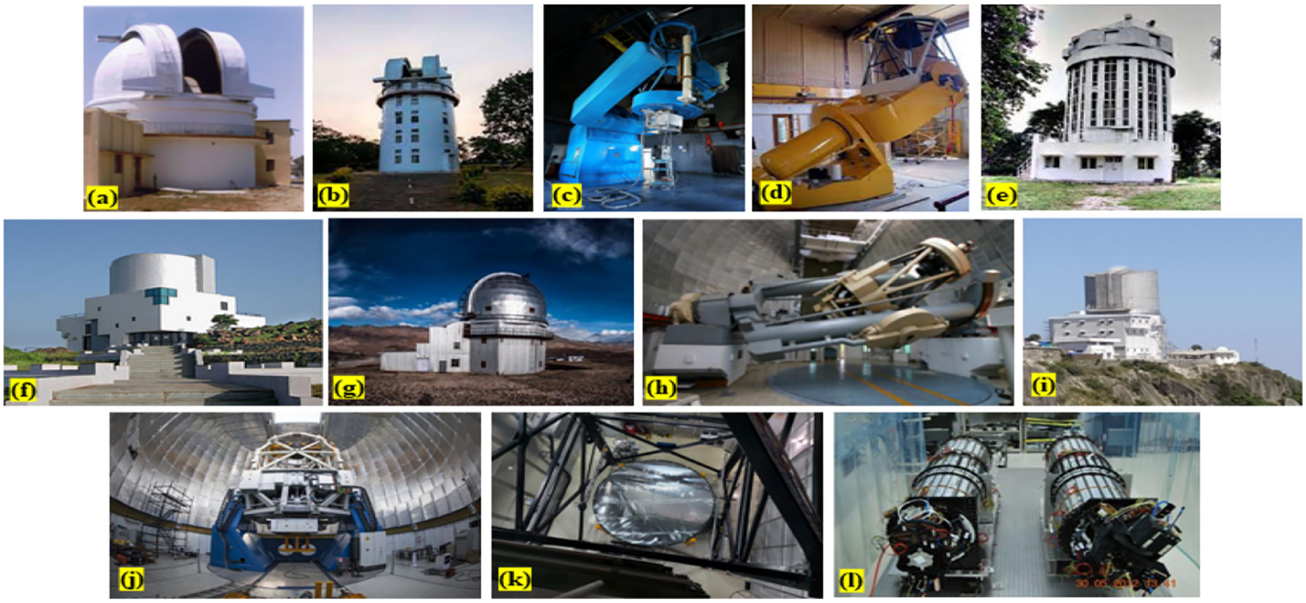

Figure 4. Optical-infrared telescopes in India: (a) Sampurnanand Telescope (1-m, ARIES, Nainital, 1972; (b) 1-m telescope (IIA, Kavalur, 1972); (c) 1.2-m (PRL, Mt. Abu, 1994); (d) 1.3-m telescope (ARIES, Devasthal, 2009); (e) 1.3-m JCBT (IIA, Kavalur, 2014); (f) 2-m telescope (IUCAA, Girawali, 2006); (g) 2-m telescope (HCT, Hanle, 2000); (h) 2.34-m Vainu Bappu Telescope (IIA, Kavalur, 1986); (i) 2.5-m telescope (PRL, Mt. Abu, 2022); (j) 3.6-m Devasthal Optical Telescope (ARIES, Devasthal, 2016); (k) 4-m International Liquid Mirror Telescope (ARIES, Devasthal); (l) Ultraviolet Imaging Telescope (2015).

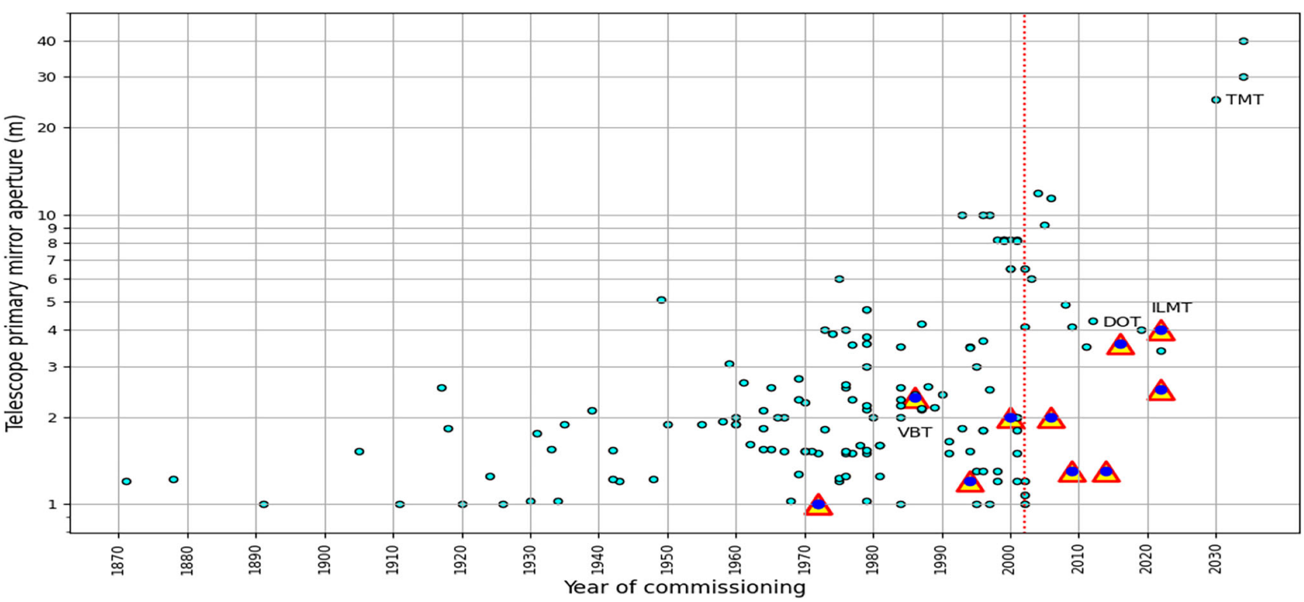

Figure 5. Aperture size and the year of commissioning of the telescopes worldwide (credit: https://en.wikipedia.org/wiki/) and those for the Indian telescopes.

of building our 10-m class telescope. For instance, India has now acquired the technological know-how in mirror making and polishing, segmented mirror technology – segment support, its control system, developing observatory, and telescope control system software, designing and developing high-precision science instruments by entering into this international collaboration. It is important to realize that the role played by 10 m class telescopes in the era of the 20–30 m telescopes will be similar to the current 2–4 m class telescopes.

While TMT will be used to address specific front-line problems, 10-m class telescopes will act as the main workhorse for most astronomical issues. Additionally, it will also act as a test-bed for future instrument prototyping. India cannot use the TMT effectively without a 10 m class telescope as it would be a big leap for the Indian astronomy community from 1–4-m to 30-m class telescopes.

Demand for a National Large Optical-infrared Telescope (NLOT) was made on several occasions with consensus on some of its general design aspects like the segmented primary, the wavelength coverage, field-of-view, requirement of adaptive optics, and tracking and pointing accuracy. As per the community requirement, the NLOT would be of a general purpose telescope (Anupama *et al.* 2022), one that can host several instruments capable of conducting imaging as well as spectroscopic (single-slit and/or multi-object and medium and/or high resolution, spectropolarimetry) modes of observations. NLOT can be designed to be the largest 10-m class telescope with an effective aperture of 13.25m in diameter. The initiation of Prototype Segmented Mirror Telescope (PSMT) for technology demonstration in the phasing of the segments (Jacob *et al.* 2022) and our proposal for involvement in building the TMT were to gain the required technological know-how to build larger telescopes on Indian soil.

Indian researchers rely heavily on the ten 1–4-m class telescopes available within the country. This may be why we have yet to conduct an all-sky spectroscopic survey in the optical wavelengths, as this would require dedicated facilities for at least ten years (if not more) for efficient sky coverage. However, to be competitive, to make meaningful discoveries, and to have a deeper understanding of the physics of the Universe, the Indian community should also plan to conduct a deep spectroscopic survey of the targets cataloged or would be cataloged by the surveys like LSST, Euclid, and WFIRST. The existing or upcoming spectroscopic surveys are limited by sky coverage, sensitivity, and survey efficiency, thus mapping only the tip of the iceberg. A 6.5–8-m class spectroscopic survey facility with a wide field-of-view of 2–4 sq. deg, highly multiplexed ($\sim$8000 fibers) employing multi-object spectrographs (MOS) for point sources and integral field units (IFU) for extended objects and combination of MOS+IFU within the same field to map ISM, stars, metal abundances, etc., in galaxies in optical and IR wavelengths is of utmost importance to the astronomical community. Such a facility will provide millions of spectra per year, reaching $r < 23$ mag at a 10σ level in just 1-h integration time. This will further identify exciting objects that could then form targets for the TMT, helping us unravel the mysteries of the fainter Universe.

Look at the highly multiplexed, wide-field optical multi-object spectroscopic programs on 4–8-m class telescopes. They have a wide wavelength coverage and spectral resolution over the optical wavelength range for which India has no direct access till today (e.g., PFS, 4MOST, DESI, MOONS, SDSS V, etc., also see Figure 3). Most of these upcoming surveys do not cover the NIR wavelength required for conducting detailed research on high-redshift objects (see Figure 3). Establishing collaborations with the US-led efforts through our TMT participation to access more data is desirable (e.g., buying time or exchanging resources and design with observing time, etc.). Note that India is a partner in building the TMT only at a 10% level. It would be challenging for the entire Indian astronomy community to spend much time observing the TMT. However, our participation in the TMT will help the Indian industry and institutes bridge the technological gap and obtain the necessary know-how to set up large indigenous telescopes in India. Also, collaborating with the Maunakea Spectroscopic Explorer (MSE project still awaits formal approval) would be scientifically highly beneficial. MSE is an 11.25-m aperture telescope that will lead the world in multi-object spectroscopy with its unique capability to study up to 4,000 astronomical objects simultaneously.

Extensive sky surveys are available from the radio domain to X-ray wavelengths, but such surveys, whether imaging or spectroscopy, are conspicuously absent in the UV range. GALEX was the only mission that performed an all-sky imaging survey, a deep imaging survey, and a survey of 200 galaxies nearest to the Milky Way galaxy. Large UV missions are currently under discussion within the astrophysical community and at the significant Space Agencies to fill this gap. India, with a robust space program for more than half a century, has demonstrated the capability to launch and operate space observatories through the successful operation of the AstroSat for seven years in orbit. UVIT onboard AstroSat has produced significant scientific results over the past seven years. It is time to enhance our space footprint by launching more extensive space facilities. The future planned missions in the optical to IR wavelengths like the Euclid and WFIRST are designed to perform imaging surveys at an unprecedented spatial resolution of $0.1''$–$0.2''$. Investing in the UV wavelength range would be prudent to synergize with these future missions.

A detailed proposal for a next-generation UV-optical mission, the INdian Spectroscopic and Imaging Space

Telescope (INSIST), submitted to the ISRO, will be the first step in this direction. The INSIST with a large focal area is expected to conduct imaging (0.1″–0.2″) survey and moderate resolution spectroscopy (slitless and multi-object). It is expected to reach a depth of $m_{\rm AB} \sim 26$ mag in imaging and $\sim$20 mag in spectroscopic modes, respectively, in the UV range. The mission, once approved, is expected to be launched in a five-year timeline. On a longer timescale, India should develop a 6-m class UV space mission operational at L2 to perform follow-up multi-object spectroscopy of targets to be cataloged by the Euclid and the WFIRST at 0.1″–0.2″ spatial resolution.

4.3 *Requirements/recommendations*

4.3.1 Developmental projects over the next 3 years

1. Initiate efforts to implement adaptive optics (AO) systems in the existing optical-IR telescopes. The feasibility of re-locating and re-installing the ROBOAO system currently installed at 2-m IGO to 2-m HCT can be considered an immediate activity. If successful, improved versions of the ROBOAO system can be installed in other 2–4-m class telescopes.
2. Develop instruments (fully or partially) for international facilities to obtain observing time in exchange, like the SCALES with KECK and ROBOPOL on Skinakas 1.3-m telescope, ROBOAO with Palomar, etc. SCALES, a precursor instrument to PSI on TMT for exoplanet spectroscopy, is a good example in which IIA is part of the team developing the complete imager, calibration system, and IFS filter wheel and in exchange, IIA utilizes some percent of observing time at Keck.
3. The construction time of a 10-m class telescope will be at least ten years, implying that the Indian community will be devoid of access to a bigger facility. To mitigate this, India should seriously pursue buying time in facilities like SALT, Subaru, Keck, LSST, etc., or exchange time by providing technology support/design new instruments, hardware maintenance, software, human resources, etc.
4. Collaborations with MSE, DESI, GTC, etc., should be explored.
5. Upgradation and efficient use of existing optical-IR telescopes in the country should move towards establishing a single TAC and astute observing methods by employing adaptive and queue scheduling. A single TAC to be constituted, adaptive, and coordinated scheduling should be initiated for 2.5-m PRL, 2-m HCT, 2.3-m VBT, 3.6-m DOT, and 4-m LMT telescopes for efficient use of telescope time, data collection and dissemination.
6. Initiate monitoring of several high-altitude trans-Himalayan regions to evaluate and identify potential sites for future optical/NIR telescopes, an exercise that was carried out some twenty years back, resulting in the identification of the Hanle site.

4.3.2 Observation facilities over the next 3–7 years

1. Design and development of advanced instruments for the existing 1–4-m class telescopes like multi-object fiber-fed or slit spectrographs, wide-field Optical-IR imaging polarimeter, spectropolarimetry, etc.
2. Automation/robotization of existing telescopes for efficient utilization of observing time.
3. The sky/atmospheric conditions of some observatories have deteriorated over the past decades. To circumvent this, efforts should be made to relocate facilities to good astronomical sites. For example, efforts to be put in and feasibility studies need to be performed to move 1-m JCBT telescope optics and its back-end instruments from VBO, Kavalur, to the Hanle site.
4. Visible and IR light collected by any telescope larger than $\sim$20 cm are blurred by distortions created due to atmospheric turbulence. Till today, none of the Indian telescopes have an adaptive correction installed in them. Adaptive optics (AO) technology for one of the existing 2–4-m class telescopes would be a prudent exercise over the next 5–7 years as part of a technology demonstration exercise for larger telescopes.
5. Complete realization of INSIST, Exomoon missions, National Large Solar Telescope (NLST), etc., are to be spearheaded as a high priority.

4.3.3 Vision for the next 10 years or beyond

1. A 6–8-m class fully automated spectroscopic survey telescope with a wide field-of-view and high multiplexing capabilities covering near-UV to near-IR providing -low, -med, -high-resolution spectra of billion point and extended sources along with Integral Field Spectrograph (IFS) capabilities is highly desirable to bridge the gap between upcoming imaging surveys and the dearth of spectra. Note that less

than 10% of all point sources detected in Gaia have spectra.

2. 12–13-m class National large optical/near-infrared (NLOT) telescope with Adaptive Optics capabilities – A continuous effort has been made towards this over the past two decades, and it is time that the astronomers in the country should come together, strongly, to realize this goal. Several Southeast Asian countries/Australia/Thailand, etc., can be involved in the design and construction of the telescope either in-kind or through the exchange of nights as the Eastern Hemisphere completely lacks such a large facility now, and collaboration would be a win-win situation for both parties.
3. 6-m space-based UV-Optical-IR telescope – JWST covers wavelength range from 5000 Å to 25 μm and has an expected lifetime of 10–15 years. This would be when India should launch a 6-m class telescope in space covering a wider wavelength range from UV-optical-IR equipped with advanced instrumentation and MOS and IFU capabilities.
4. 2-m telescope at an Indian base in Antarctica – Maitri or Bharati is the existing Indian base situated at Latitudes of 69–70° S and Longitudes ~79° E. Six months of complete sky coverage is available for astronomers which is wishful for continuous monitoring of transient objects. Observable declination ranges are $-10°$ to $-89°$. 1–2-m class telescopes should not be an immediate choice at this juncture for Indian astronomy. Still, a 2-m telescope in Antarctica would be desirable if we installed more small aperture-sized telescopes.

4.3.4 Technological challenges We have identified a few technologically challenging areas for India. If the technologies listed below are established within the country, we will be at the forefront of building world-class facilities.

1. Mirror-making technology – capability exists within the country for grinding and polishing, fabricating segment supports, actuators, and other control systems for fabricating mirrors; expertise exists for aligning and phasing the segmented mirrors except for Ion beam figuring. This technology is employed after stressed mirror polishing and improves the surface accuracy of a mirror to the nanometer level necessary for diffraction-limited performance. This technology needs to be developed in the country within the next 5 years.
2. Large optics fabrication – Wider field-of-view is achieved by employing a system of lenses that corrects for off-axis aberrations, allowing the telescopes to provide excellent image quality over a very large field. It is challenging to fabricate these corrector lenses as a few have extreme freeform optics. Indian institutes and industries should work together to acquire fabrication capabilities of corrector lenses of sizes greater than 500 mm–1.5 m, which is badly needed if we require wide-field data. Again, several large optics form the spectrographs: gratings, collimators, and dichroics. With the increase in the telescope aperture's size, the instruments' size also increases, requiring optics ranging from 300 mm to 1.5-m. Currently, the country is severely limited in fabricating large optics that need nourishment.
3. Fiber positioners – A new and automated way of providing the whole map of the observable Universe requires high multiplexing of fibers with shorter reconfiguration times. All the upcoming surveys will use robotized positioning systems with 1000–5000 fibers. Some fiber positioner technologies are Echidna fiber employed at 4MOST, COBRA fiber technology employed at PFS, and AAO's Starbugs technology employed by PHOBOS/Keck spectrograph, etc. Our telescopes work with a single or small number of fibers but have never employed large fibers or fiber positioners – a huge technological gap between the world and India. A few fibers and a fiber positioner system must be built as prototypes in the next 3 to 5 years.
4. Enabling astrophotonics: The size of the back-end instruments scales linearly with the size of the telescope. This complicates the design and inflates cost quadratically. Integrated photonic components can be employed efficiently to miniaturize the instruments. Tapered fiber devices known as photonic lanterns – with their ability to convert multimode into single-mode optical fields – can be used to feed speckle patterns into single-mode integrated optics. Combined with photonic lanterns, low-order adaptive optics offer a practical approach to achieving efficient coupling into multiplexed astrophotonic devices. Using photonic lanterns may reduce the multiplicity of multiplexed integrated instruments (Diab *et al.* 2021). Researchers have found ways to couple multicore optical fibers with Fibre Bragg Gratings (FBGs) to create photonic lantern filters that smartly act as ultra-narrowband line blockers that can have multiple uses, e.g., in NIR spectroscopy of highly crowded fields and exoplanet transit spectroscopy (Bland-Hawthorn *et al.* 2011;

Birks *et al.* 2012). This technology is still new, and its applications have only recently been realized in astronomy. Indian industries and Indian research labs can come together to develop efficient fiber-coupling technologies.

5. Development of astronomical instruments for ground and space telescopes based on digital micromirror device (DMD) like the MOS under development for the INSIST mission. Also, the development of CMOS and CCD detectors, IR arrays, and their controllers within the country.

5. Infrared astronomy observation facilities

5.1 *Next-generation observation facilities – World vision*

The infrared wavelength window gives us visibility to everything from the far away high redshift universe to the nearby dust-obscured star-forming regions in our own Galaxy. The infrared facilities have thus become the primary tools of humanity to understand the origins of the universe, dark energy, stars, or planets. The recently launched 6-m James Webb Space Telescope (JWST), in many ways, represents the pinnacle of IR wavelength's space frontier in the last decade. Before JWST, various space-based missions like Spitzer, Herschel, WISE, etc., made groundbreaking discoveries in all areas of astronomy, from nearby exoplanets to far-away cosmic dawn science questions. On the space front, the upcoming optical to near-infrared mission ARIEL will enable transmission spectroscopy of numerous exoplanet atmospheres. The SPHEREx mission will do an all-sky low-resolution spectroscopy mapping near to mid-infrared. Euclid space mission will enable extra galactic near-infrared imaging and spectroscopy of high redshift galaxies. Roman (WFIRST) space telescope will allow large areas of near-infrared imaging and high contrast space-based coronagraphy to image large orbit exoplanets. Future NASA Flagships missions like LUVOIR, HabEx, and Origins Space Telescope have infrared components. However, it is too early to know which among them will get merged/downsized/funded. Upcoming balloon-based observatories like GUSTO will study specific lines in the interstellar medium by far-infrared high-resolution spectroscopy. In summary, the space frontier in the forthcoming decade will open up deep, wide field-of-view imaging and low/medium resolution spectroscopy in near-infrared and mid-infrared. No high-resolution spectroscopy, polarimetry, or far-infrared facilities are coming up in space in the upcoming decade. On the ground frontier, many modern instruments are coming up near-infrared across the world's Optical IR telescopes. With the rise of transient astronomy and wide-area surveys, imaging capabilities have gone far ahead of spectroscopic follow-up capabilities. Only a tiny fraction of LSST transient alerts are expected to be possibly followed up spectroscopically. To catch up, multi-object spectrographs of various architectures are being built on almost every large telescope. Upcoming spectroscopic surveys (limited mainly by fiber technology) go only up to 1.8 microns (e.g., PFS). Spectrographs that cover longer wavelengths exist (e.g., SPIROu) but are not for a large field-of-view survey. Using near-infrared adaptive optics front end, many new high spatial resolution spectroscopy instruments are being built on Keck, VLT, etc. All the upcoming 30-m class telescopes (ELT, GMT, TMT) have near-infrared deep imaging and spectroscopic instruments planned in the first generation. Ultra stable, high-resolution near-infrared spectrographs for habitable zone exoplanet detection around M dwarfs (majority of stars in our solar neighborhood) and for measurement of the fundamental constants across cosmological scales are already built and being built. Near-infrared interferometry facilities like CHARA and GRAVITY/VLTI have significantly matured in technology and have started producing large volumes of previously unattainable sub-milliarc second spatial resolution observations of bright targets. In the adaptive optics frontier, there is a push to achieve even wider area AO systems to enable high spatial resolution observations. The advent of cheaper low-noise high-speed cameras has also enabled speckle imaging facilities like NESSI on telescopes without AO capabilities.

5.2 *Current facilities in India*

India currently has multiple medium size near-infrared and far-infrared facilities. Among the optical telescopes in India, most are also suitable for near-infrared observations. The current facilities we have in India are listed in the following sections.

Near-infrared imaging

- NICS on 1-m Mount Abu Telescope. J, H, K, and narrow band filters in near-infrared.
- TIRSPEC on 2-m Himalayan Chandra Telescope, Hanle, IAO. J, H, K, and narrow band filters in near-infrared.

- TANSPEC on 3.6-m Devasthal Optical Telescope, Nainital, ARIES r, i, J, H, K, and narrow bands in optical red to near-infrared.
- TIRCAM2 on 3.6-m Devasthal Optical Telescope, Nainital, ARIES J, H, K, L′. It can observe up to 3.6 microns (L′).

Near-infrared spectroscopy

- NICS on 1-m Mount Abu Telescope. Resolution ∼1000, Wavelength range 1 micron to 2.5 micron.
- TIRSPEC on 2-m HCT. Resolution ∼1200, Wavelength range: 1 micron to 2.45 micron.
- TANSPEC on 3.6-m DOT. Resolution ∼2500, Wavelength range: 0.55 micron to 2.5 micron.

Mid-infrared facility

Currently, India does not have any mid-infrared facility. TIRCAM2 on 3.6-m DOT is the longest wavelength camera which can image up to 3.6 micron.

Far-infrared facility

- T100: 1 meter Far-infrared Balloon platform telescope from TIFR Balloon Facility. It carries a Fabry Perot Single Pixel Spectrograph (FPS), used to generate spectroscopic maps of 158 micron [C II] lines of high mass star forming regions.

5.3 *Developments over the next 3 years*

Upcoming near-infrared facilities in India over the next 3 years:

Near-infrared

- Updated TIRSPEC on HCT. Upgradation work on TIRSPEC is currently ongoing to increase the sensitivity of TIRSPEC by replacing the existing HAWAII-1 PACE array with a more advanced H1RG detector.
- Near Infrared Spectrometer and Polarimeter (NISP): This upcoming instrument will have near-infrared imaging (10×10 arcmin^2), spectroscopy ($R \sim 2000$) and imaging polarimetry capabilities on the 2.5 m PRL telescope.

Far-infrared

- The backend instrument FPS on the T100 Far infrared telescope is currently being upgraded from a single pixel FPS to a 5×5 pixel array and higher resolution ($R \sim 6000$) FPS for [C I] line mapping.

5.3.1 Recommendations for the next 3 years To increase the efficiency and science output of the existing facilities, we recommend the following:

- Standardization of the data formats and headers of different instruments in the country. This will make it easier for astronomers to work on multiple instruments without the extra overhead of modifying their data reduction codes for every instrument.
- Development of pipelines for instruments that currently do not have standard pipelines. This can be a community-driven approach, and we recommend setting up software standards that everybody can follow to guarantee code reuse and maximum interoperability. Most international observatories like Keck and ESO telescopes already follow these practices.
- Setup of the centralized, searchable data archive. Indian observatories have collected excellent data over the last few decades, and having a central repository for all infrared and optical data will enable more science out of the existing data.
- Setup Queue scheduled nights on all Indian telescopes to enable optimal use of best observing conditions for the highest priority science. It will also enable new kinds of multi-cadence observations.
- Set up an instrumentation resource-sharing network to enable multiple instrumentation teams in the country to share resources.
- Most recommendations already listed in the UV/optical section also apply to near-infrared facilities.

5.4 *Facilities over the 3–7 years*

Upcoming near-infrared facilities are currently being developed for Indian telescopes.

Near infrared

Two multi-object spectrographs are currently being built for 3.6-m DOT.

- MOIS: A configurable slit multi-object near-infrared spectrograph for high throughput observations ($R \sim 2500$).
- TA-MOONS: A deployable multi-object slit spectrograph with simultaneous wavelength coverage from optical 350 nm to 2.5 micron ($R \sim 2500$) for conducting large spectroscopic surveys.

Mid-infrared

- IRSIS: Mid-infrared all-sky spectroscopic survey satellite will cover all sky at a low or medium resolution.

5.4.1 Recommendations for the next 3–7 years To fill clear gaps in Indian infrared facilities, we recommend the following:

- Robotization of small telescopes to enable fast follow-up studies and high-efficiency observations.
- Setting up more robotic telescopes in the country with instruments like multi-band hypercams and precision near-infrared photometry cameras.
- Near-infrared spectro-polarimetry capability is something we should develop in our country. We already have experience in the country with optical polarimeters, so it will be relatively easy to extend this capability to near-infrared.
- Adaptive optics imaging capability on near-infrared telescopes.
- General purpose Infrared Balloon Observatory platform. India has a long heritage and expertise in world-class scientific ballooning. High-pointing stability Optical to Infrared telescope on the Balloon platform will enable the Indian community to do significantly cheaper, near-space quality measurements with the added benefit of customizability of the instrument for every flight.
- Until we have our own 10-m class telescopes in India, we should consider joining consortiums of large aperture telescopes worldwide with infrared instruments.

5.5 *Vision for the next 10 years*

India's longitude is far from other major observatories like Hawaii and the Canary Islands, and we have high-altitude sites like Ladakh, which have many clear nights per year. This exclusive access to temporal parts of the sky, which are inaccessible to other major facilities, gives us a strong advantage in many fields like the time domain astronomy and transient follow-ups. We should build our proposed 10-m class optical-infrared telescope (NLOT) and infrared backend instruments to enable cutting-edge observational astronomy research in the country. The pathfinder infrared instruments that we develop keeping future large telescopes in mind, can naturally become the next generation cutting edge instruments in the existing 2–4-meter class telescopes. We currently lack both high spatial and spectral resolution capability in near-infrared. We should develop the country's AO, image slicer, and coronagraph capabilities to enable high spatial resolution science cases. Furthermore, we could potentially use the flat terrains of Ladakh for long baseline optical/infrared interferometry facilities. One way to bring in new technology is to invite international partners to set up facilities on Indian sites; this will provide training and experience in building more advanced, state-of-the-art instruments. Apart from near-infrared, the high-altitude Ladakh sites are likely excellent for N band (10 microns) observations. Currently, India lacks any mid-infrared N band facilities. This will be a unique capability for India to develop over the next decade. Thanks to India's ballooning heritage, we have a unique advantage in doing cutting-edge infrared observations in the wavelength bands blocked by our atmosphere. Balloon platforms enable us to develop target and specific science-optimized backend instruments for each flight. India currently has zero-pressure balloon technology. Developing our super-pressure ballooning technology expertise will allow us to have weeks/month long flights from India's Antarctica station. Access to ISRO provides us with a unique advantage on the space frontier. So far, all astronomy space missions from ISRO have been high-energy observatories. We have not had a cooled payload infrared observatory yet. Developing this cooling technology for space payloads will enable India to enter the frontier of cutting-edge infrared space observatories.

6. Radio astronomy observation facilities

6.1 *Next-generation observation facilities – World vision*

The study of the celestial sky in the radio frequency spectrum includes radio continuum emission from stars, compact objects, AGN, galaxies, galaxy clusters, HI 21-cm line or molecular lines from redshifted sources, time-domain sources like pulsars, and fast radio bursts. There are many radio telescope facilities covering different parts of the radio frequency spectrum starting from large single dishes like the Parkes in Australia, Green Bank Telescope (GBT) in USA, Effelsberg in Germany, Sardinia in Italy, and the Five-hundred-meter Aperture Spherical Telescope (FAST) in China to array instruments such as the Murchison Widefield Array (MWA) and Australian Square Kilometre Array Pathfinder (ASKAP) in Australia, Low-Frequency Array (LOFAR) in Europe, Ooty radio telescope (ORT) and Giant Metrewave Radio Telescope (GMRT) in India, MeerKAT in South Africa, Very Large Array (VLA) and Long Wavelength Array (LWA) in USA, Canadian Hydrogen Intensity Mapping Experiment (CHIME) in Canada. In addition, the very long baseline array telescopes, formed using individual observatories over continental baselines, provide ultra-high resolution radio images. The Very Large Baseline Array (VLBA) in the USA, the European VLBI network (EVN), the East Asian VLBI network, and the Event Horizon Telescope (EHT) are some of them. The Square Kilometer Array (SKA) project (with the completion of Phase-1 towards the end of the present decade) is a state-of-the-art, global project that aims to build the biggest and most sensitive radio telescope for delivering a wide range of cutting-edge science results. Indian astronomers regularly use these facilities and actively contribute to building SKA Phase-1, which will boost Indian capability and train people to create next-generation telescopes in India.

6.2 *Upcoming facilities in India*

The GMRT (Swarup *et al.* 1991) is an indigenous, world-class facility operating over a frequency range of 120–1460 MHz. Aided by its recent upgrades, the uGMRT (Gupta *et al.* 2017) is recognized as one of the SKA pathfinders providing wider (200/400 MHz) instantaneous frequency band coverage. Operating in a highly competitive bi-annual open proposal reviewing system, the observing time requests with the uGMRT is always a factor of two or more over-subscribed. Moreover, the ORT is also currently undergoing a major receiver upgrade (Ooty Wide Field Array, OWFA, Subrahmanya *et al.* 2017), which is aimed to enhance the instantaneous bandwidth as well as provide a significantly larger field-of-view compared to the legacy ORT receiver system. The uGMRT's enhanced sensitivity is expected to contribute substantially to the global VLBI experiments. It is imperative to develop effective ways to maintain the performance of the GMRT close to its design specifications and preserve its status as a globally attractive microwave instrument. It means dealing with Radio Frequency Interference (RFI) and protecting radio-quiet locations. The current implementation of the real-time threshold-based filtering system (Buch *et al.* 2016) is undergoing architectural optimization and the scope of adding new algorithms to perform better in the growing RFI environment. The Gauribidanur radioheliograph is the only one dedicated to solar observations at low frequencies (<100 MHz) in India or elsewhere. With the upgrade, the Gauribidanur instrument can be used as a dedicated facility for observing non-solar transients at night.

6.3 *Developments over the next 3 years*

- SPOTLIGHT: The uGMRT's excellent collecting area and imaging resolution can contribute significantly to transient sciences. The SPOTLIGHT project, funded by the National Supercomputer Mission (NSM) under MeitY and DST of Govt. of India, enables exploring a completely new programming paradigm both in HPC and in AI to leverage GMRT's potential in delivering cutting-edge time-domain astronomy transient sciences. This commensal system powered with petaflops computing and petabyte storage aims to discover a large population of FRBs associated with its host galaxies and pulsars over the next few years.[3]
- InPTA: The International Pulsar Timing Array (IPTA) program is designed to detect the stochastic GWs background using high-precision timing of a set of millisecond pulsars (MSPs). The uGMRT, being an IPTA telescope, can provide sensitive low-frequency timing measurements via the Indian PTA (InPTA)[4] monitoring program. The uGMRT with excellent low-frequencies (i.e., <1 GHz) observing capability provides a sensitive probe for monitoring the interstellar medium (ISM) and its temporal evolution to mitigate adverse effects in the arrival times (Hassall *et al.* 2012) which are embedded in the high-frequency measurements.
- VLBI: Expansion of observing parameter space of the uGMRT by establishing Very Long Baseline Interferometry (VLBI) capabilities and extending the frequency coverage to S/C/X bands provide unprecedented probes for accretion physics.

[3] https://spotlight.ncra.tifr.res.in.

[4] https://inpta.iitr.ac.in.

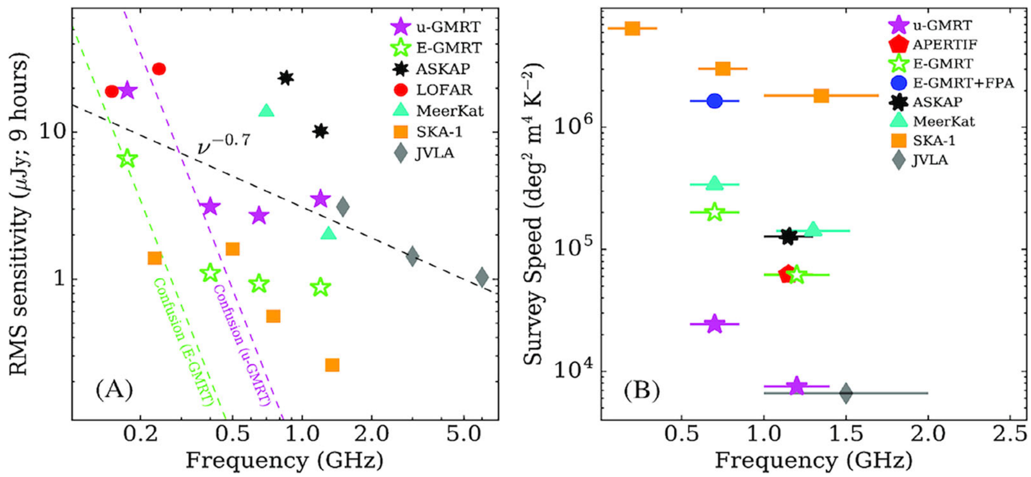

Figure 6. Left panel: The continuum sensitivity of the eGMRT compared with that of the other radio interferometers (the uGMRT, the JVLA, LOFAR, MeerKAT, ASKAP, and the SKA-1) for a 9 h full-synthesis integration. The green and magenta dashed lines show the 1σ confusion noise for the eGMRT and the uGMRT at the different observing frequencies. The eGMRT's confusion limit (green stars) will be significantly lower than the theoretical sensitivity. The eGMRT is close to the SKA-1 sensitivity for frequency <1 GHz. Right panel: The survey speed figure of merit, in deg^2 m^4 K^{-2} (Patra *et al.* 2019 and references therein), of the eGMRT compared with that of other present or planned radio interferometers. For the eGMRT, we have considered two possibilities: the open green stars refer to single-pixel feeds, while the solid blue circles assume FPAs covering 550–850 MHz installed on the 45 antennas within the central square (figure credit: Patra *et al.* 2019).

- The OWFA completion will significantly enhance ORT's capability in newly emerging research areas like 21-cm intensity mapping and studies of transient radio sources.
- Up-gradation of Gauribidanur radioheliograph will enable joint observations of the solar corona at frequencies <100 MHz (in both Stokes-I and Stokes-V modes) along with VELC onboard ADITYA-L1.
- The experiments related to the CMB polarization science and recombination lines warrant developing facilities for cryogenic instrumentation, bolometers, and low-noise amplifiers.
- Space Electric and Magnetic Sensor (SEAMS), a mission operating at the low-frequency (300 kHz to 16 MHz) aims to study radio emissions from the Sun, planetary and exoplanetary magnetosphere, the galactic spectrum at low frequencies, and the red-shifted 21 cm line from the early Universe, which is now at its Phase-1 for mounting the payload on the fourth stage of PSLV and placed in the Low Earth Orbit (LEO).

6.4 *Facilities over the 3–7 years*

- The expansion of the GMRT facility (eGMRT, Patra *et al.* 2019) will significantly enhance the low-frequency radio astronomy capabilities in the country, keeping it relevant in the era of SKA Phase-1. The eGMRT will enhance the collecting area by adding more antennas and will increase the instantaneous field-of-view from the Focal Plane Array (FPA). Also, the possibility of increasing resolution (and hence the confusion limit) by adding longer baselines will be explored. Figure 6 shows that with a two-three fold increase of the collecting area, eGMRT can provide comparable sensitivity to the SKA Phase-1 for frequencies <1 GHz. Moreover, with a 30-beam FPA operating at 550–850 MHz, the field-of-view increases to $15^{\circ 2}$, providing many fold higher survey speed than the existing interferometers.
- The uGMRT capability can be further enhanced by adding a band-1 (30–80 MHz) receiver constraining the energetic impact of radio-loud active galactic nuclei on the universe over cosmic time as well as probing global 21-cm signal from cosmic dawn and epoch of reionization.
- Large-scale CMB telescope operating with cryogenically cooled superconducting bolometer detectors at a high altitude and quiet site facilitates CMB polarization science.
- Space-based radio astronomy experiments like Probing ReionizATion of the Universe using Signal from Hydrogen (PRATUSH), SEAMS Phase-3 enabling observations from the lunar far

side devoid of terrestrial RFIs can detect the weak cosmological signals.

6.5 *Vision for the next 10 years*

- The eGMRT project, with its full completion and access to the SKA Phase-1 facility, will enable Indian scientists to perform cutting-edge research while leading in building the future expansion of SKA (Phase-2).
- With very active developments for space VLBI missions, India can be at the forefront of the modern era's international radio astronomy space race.

7. Submm astronomy facilities

Sub-millimeter (sub-mm) bands ($\nu \approx 30$–1000 GHz) have unique spectral signatures of the Universe's coldest and densest gas and dust structures on all scales. The sub-millimeter bands bear imprints of the cosmic microwave background, starburst galaxies over cosmic time, star-forming regions, and planet-forming disks. From the discovery of dusty sub-mm galaxies in the early Universe through to the ringed nature of protostellar disks, our understanding of the formation, destruction, and evolution of objects in the Universe has and will continue to require a comprehensive view of the sub-mm sky.

Sub-mm observatories are located in cold high-altitude locations with low ($<$2 mm) levels of precipitable water vapor (PWV) in the atmosphere since the water molecule both absorbs the radiation from the celestial objects and re-emits it, creating an extensive background. The currently operational telescopes include single-dish facilities such as the 15-m James Clerk Maxwell Telescope (JCMT) in Hawaii, IRAM 30m in Granada, Spain, Atacama Pathfinder EXperiment in Chile, and 50-m Large Millimeter Telescope (LMT) in New Mexico as well as the interferometric arrays such as the Atacama Large Millimeter/sub-millimeter Array (ALMA) in Chile, the Northern Extended Millimeter Array (NOEMA) in France and the Submillimeter Array (SMA) in Hawaii. Many of these facilities have receivers and new data processing algorithms that enable them to join as Very Long Baseline interferometers like the VLBA and EVN networks to create the Event Horizon Telescope (EHT).

India so far does not have a sub-mm observing facility. However, there is a growing community of astronomers working in the area of the interstellar medium and star formation requiring access to such a facility. In the short- and mid-term, a 6-m sub-millimeter telescope with single-pixel receivers operating at 230/345 GHz and backend digital spectrometers with an instantaneous bandwidth of 4 GHz and a resolution of 1 MHz will be installed at the IAO site (4500 m) by SAC-ISRO, Ahmedabad. Receivers with higher frequency ($>$500 GHz) capabilities are planned as second-generation instruments. Complementing the current efforts in building the 6-m sub-millimeter telescope, the Indian Astronomy institutes are collaborating to monitor multiple Himalayan sites at altitudes $>$5000 m to check their suitability as sites for sub-millimeter telescopes. The vision for the next 10 years would be to develop a sub-mm site for world-class observatories in the Himalayas at altitudes exceeding 5000 m and build an internationally frontier-defining 15 m class Indian sub-mm telescope. The development of such a facility in a site that is capable of observations at frequencies up to 1.1 THz will make it unique in the northern hemisphere. The proposed observatory in the Himalayas would also add a new location to the global network of telescopes, which operate synchronously to synthesize the EHT.

7.1 *Existing and planned observation facilities – World vision*

The location of the sub-mm observatories is decided by the levels of precipitable water vapor (PWV) in the atmosphere since the water molecule absorbs the radiation from the celestial objects and re-emits it, creating a large background. Thus, sub-mm facilities currently operational and planned for are located either at high-altitude or in extremely cold and dry (PWV $<$ 2 mm) regions (e.g., Antarctica) or on stratospheric aircraft or balloons.

Atacama Large Millimeter/sub-millimeter Array (ALMA) is currently the world's largest ground-based sub-mm astronomical observatory with 66 antennas spread over distances up to 16 km, operating between 80–950 GHz. The Northern Extended Millimeter Array (NOEMA) is one of the largest radio telescopes in the Northern Hemisphere, operating at millimeter wavelengths. It consists of a large array of twelve 15-meter antennas that can spread over distances of up to 1.7 km, working together as a single telescope. The Submillimeter Array (SMA) is an 8-element radio interferometer located near the summit of Maunakea in Hawaii. Operating at frequencies from 180 to 420 GHz, the 6 m diameter dishes may be arranged into configurations with baselines as long as 509 m.

The very principle of interferometry implies that these observatories, though excellent in peering into the details in limited regions, cannot capture the emission from large-scale structures. The interferometers also cannot carry out large-area unbiased surveys as efficiently as their counterparts. Facilities such as the 15-m James Clerk Maxwell Telescope (JCMT) in Hawaii, IRAM 30m in Granada, Spain, have been the workhorses in the sub-mm for decades, with newer facilities such as Atacama Pathfinder EXperiment in Chile and the 50-m Large Millimeter Telescope (LMT) in New Mexico adding to our understanding of the large-scale structure in the sub-mm sky. Many of these facilities have receivers and new data processing algorithms that enable them to join as Very Long Baseline interferometers like the VLBA and EVN networks and the EHT.

The planned sub-mm facilities include: (i) The 6-m Fred Young sub-millimeter Telescope (FYST; known as CCAT-p) being built at an altitude of 5600 m on Cerro Chajnantor accessing frequencies exceeding 450 GHz. The telescope will be equipped with a suite of instruments with wide-field mapping abilities and will likely become operational by 2024. Further in the future, beyond the 2030s, a natural extension to CCAT-p will be a large aperture (25m) version and at longer wavelengths, the 50-m single dish Atacama Large Aperture Submillimeter Telescope (AtLAST, Klaassen *et al.* 2019) at 5060 m operating at 300–1000 GHz.

Following the success of EHT in imaging the black hole shadow in M87 and the Space VLBI mission RadioAstron that operated at wavelengths down to 1.3 cm and baselines up to $\sim$30 Earth diameters leading to angular resolutions of 10 μ as a global initiative for space VLBI mission in the sub-mm and mm has also been started (Gurvits *et al.* 2022). The concept of TeraHertz Exploration and Zooming-in for Astrophysics (THEZA; Gurvits *et al.* 2021) is one of the components of this global initiative presented in the ESA Voyage 2050 White Paper.

7.2 *Upcoming facilities in India*

In the short- and mid-term, a 6-m sub-millimeter telescope with single-pixel receivers operating at 230/345 GHz and backend digital spectrometers with an instantaneous bandwidth of 4 GHz and a resolution of 1 MHz will be installed at the IAO site (4500 m) by SAC-ISRO, Ahmedabad. Receivers with higher frequency (>500 GHz) capabilities are planned as second-generation instruments.

7.3 *Developments over the next 3 years*

Complementing the current efforts in building the 6-m sub-millimeter telescope, the Indian astronomy institutes are collaborating to perform monitoring of multiple Himalayan sites at altitudes >5000 m to check their suitability as sites for sub-millimeter telescopes. The monitoring activities will be undertaken in a phased manner in which the site characterization will be started using GPS-based technology and commercially available Automated weather stations on coarse resolutions and followed up with the installation of 183/220 GHz radiometer-based water vapor monitors at fewer selected locations.

7.4 *Facilities over the 3–7 years*

The 6-m sub-mm telescope is expected to be operational during this period, and activities about building second-generation instruments for the telescope are expected to gain momentum. Weather data analysis relevant to site characterization in the Himalayas will also be a major activity for a future proposed larger sub-mm telescope.

7.5 *Vision for the next 10 years*

Develop a sub-mm site for single-pixel observatories in the Himalayas at altitudes exceeding 5000 m and build an internationally frontier-defining 15 m class Indian sub-mm telescope. The development of such a facility in a site that is capable of observations at Tera-Hertz frequencies up to 1.1 THz will make it unique in the northern hemisphere. The proposed observatory in the Himalayas would add a new location to the global network of telescopes, which operate synchronously to synthesize the Event Horizon Telescope (EHT) using the Very Long Baseline Interferometry (VLBI) technique. The EHT recently imaged, for the first time, the signature of a supermassive black hole at the center of the M87 galaxy, captivating the entire world. Participation in such a high-profile global enterprise would enhance the international visibility of Indian scientific and technological developments and provide an immense boost. The science drivers for such a sub-millimeter facility include: (i) Questions about the process and efficiency of star-formation and its impact on the galactic environment as well as turbulence in the Local Universe, (ii) Discovery of actively star-forming galaxies visible only in the sub-mm, 3D clustering of star-forming galaxies to understand structure formation, probe the underlying dark matter density fluctuations, and the Sunyayev–Zeldovich effect in the Distant Universe and (iii) Sub-mm study of exotic phenomena such as variable protostars, GRB afterglows and counterparts of fast radio bursts in the Transient Universe.

8. Gravitational wave astronomy facilities

8.1 *Next-generation observation facilities – World vision*

The detection of gravitational wave (GW) (LIGO Scientific, Collaboration *et al*. 2016) marks a new era in Astronomy, and the first few years of GW Astronomy have been eventful and exciting. Nonetheless, it is just the beginning of a new field; there is enormous scope for discovery and science (Bailes *et al.* 2021). We have observed about a hundred compact binary coalescence (CBC) events so far, while the upgraded and next-generation detectors promise to observe at orders of magnitude higher rates (Bailes *et al.* 2021). These observations will significantly improve the understanding of how and where compact objects form in the universe and their numbers, properties, distribution, etc. A network of detectors will enable precise localization of the events in the sky, significantly improving crucial Astrophysical measurements, e.g., estimation of Hubble constant, especially if there is an observable electromagnetic (EM) counterpart. The present status and prospects of GW astronomy have been nicely summarized in the GW International Council (GWIC) Roadmap published recently as (Bailes *et al.* 2021).

Three large ground-based laser interferometric detectors have detected GW signals: two 4 km LIGO detectors in the USA and the 3 km Virgo detector in Italy. These are large Michelson Interferometers with Fabry-Perot cavities in each arm enclosed in large vacuum tubes. A 3 km detector in Japan, named KAGRA, has recently joined the network. For years, a 600 m arm detector in Germany, the GEO600, has played crucial roles in technology development for large interferometers. The ground-based laser interferometric detectors operate in the ∼10 Hz to a few kHz frequency band, though Astrophysically interesting sources are present across a wide range of frequencies. These detectors are limited by unavoidable seismic noise at lower frequencies and are unlikely to acquire adequate sensitivity below a few Hz. The only option to observe lower frequency GWs is either by building space-based detectors or by observing the effect of GW on Pulsar Timing or Cosmic Microwave Background (CMB) polarization. Research and development are being actively pursued worldwide in all these directions, including improving the sensitivities of the present detectors and building next-generation ground-based detectors. The key directions are listed as follows.

- Improving sensitivities of the present ground-based laser interferometers: The sensitivities of the present detectors are being upgraded in stages, which is likely to continue for the next few years. There is a plan to introduce a major upgrade, named 'Voyager' (Adhikari *et al.* 2020), retaining the same vacuum tubes. This upgrade can be highly relevant for the planned LIGO-India detector.
- Next generation ground-based detectors: To improve the sensitivities, especially in the lower frequencies, detectors with much longer arm-lengths have been proposed, a ∼10 km arm 'Einstein Telescope' in Europe and a ∼40 km is 'Cosmic Explorer' in the USA. Site surveys and designs for both proposals are advancing fast.
- Space-based milli-Hertz detectors: A large population of binary mergers involving at least one supermassive or intermediate-mass black hole are expected to emit GW in the milli-Hertz band. Two space-based detectors for the milli-Hertz band, LISA (ESA) and TianQin (China), with order million-kilometer arm length, are being developed for launch in the 2030s. These detectors have many exciting science cases; one of the major ones will be their ability to forecast stellar mass compact binary mergers, which are going to merge in the ground-based detectors' band months to years in advance, providing major opportunities for multi-messenger astronomy (MMA).
- Space-based deci-Hertz detectors: There is a gap in the deci-Hertz band. Though there have been compelling science cases (Kuns *et al.* 2020), e.g., highly cost-effective multi-messenger astronomy aided by the overlapping frequency bands between space- and ground-based detectors that a deci-Hertz mission can introduce and a possibility to directly probe the primordial stochastic GW background (SGWB) from Cosmic Inflation (Ishikawa *et al.* 2021), and there have been technologically exciting proposals, like the BBO (USA), DECIGO (Japan), TianGO (USA/China), none of them have been funded yet. With the relevant expertise promised by LIGO-India and India's strong space program, India may be able to play a lead role here. The

feasibility of such a mission led by India, tentatively called GWSat, is being explored.

- Pulsar Timing Arrays (PTA): Pulsars are very precise clocks. A passing GW can introduce tiny fluctuations in the pulsar timing. Since these fluctuations are correlated across different pulsars, one can determine the strength of the GW signal and the source's location by observing an array of these. Several groups of radio telescopes are observing sets of pulsars for this purpose, namely, the Parkes Pulsar Timing Array (PPTA), the European Pulsar Timing Array (EPTA), and NanoGrav. The Indian Pulsar Timing Array (InPTA) was recently formed, using the upgraded GMRT (uGMRT) telescope for observations.
- Cosmic Microwave Background (CMB) B-mode polarization anisotropy: Most models of cosmic inflation, an inevitable pillar of standard cosmology, predict that the CMB B-mode polarization anisotropy embeds signatures of the SGWB generated in the early universe. This is the primary science goal for all the present and upcoming CMB ground- and space-based observatories, like Polarbear, BICEP, Keck array, and the LiteBird mission. An Indian mission named 'CMB-Bharat' has also been proposed. Determining and removing the contamination from the B-mode polarization component from the galactic dust is a fundamental challenge here.

8.2 *Upcoming facilities in India*

8.2.1 LIGO-India LIGO-India is a planned detector with 4 km arms, identical in design to the two LIGO detectors in the USA, and also envisioned to operate at the same sensitivity. This project is funded by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST), India, with a memorandum of understanding with the National Science Federation (NSF), USA. It will be executed by four lead intuitions in India: DCSEM (Mumbai), IPR (Gandhinagar), IUCAA (Pune), and RRCAT (Indore). Several key components of the detectors will be contributed by the LIGO-USA, which will bring new technical expertise to India. Being a multi-disciplinary mega-science project on Indian soil, LIGO-India can provide a common platform for knowledge exchange and collaboration between experts from various science and technology streams, namely, Physics, Astrophysics, Mathematics, Computer Science, Artificial Intelligence and Machine Learning, Laser, Optics, ultra-high vacuum, active vibration reduction, low noise electronics, precision controls, contamination control, etc.

8.3 *Developments over the next 3 years*

The LIGO-India detector will start taking science data in the next few years. Construction of the building, vacuum tubes, installation of some components, data acquisition and analysis facilities, training to build the operation and detector commissioning teams, and Education and Public Outreach will be important activities during this period. An important aspect will be contributing to international research activities to improve the sensitivities of the present detectors, which would be the target sensitivity for LIGO-India when it starts taking science data.

This is also a crucial period to determine if India wants to lead in filling the gap in GW observation in the Deci-Hertz band through the GWSat mission. Several prototype technology developments regarding this project can take place during this time, along with writing a Detailed Project Report (DPR).

8.4 *Facilities over the 3–7 years*

This period will witness some core research and development activities for LIGO-India. The complete installation of the detector is expected in the first part of this period, followed by commissioning and engineering data-taking activities. The detector will start taking science data by the end of this period.

For the envisioned GWSat mission, this will be a primary period for developing and testing the payloads.

8.5 *Vision for the next 10 years*

Once LIGO-India starts routine operation, the development teams can focus on contributing towards the next generation of ground and space-based detectors. A major part of the human resource can be devoted to completing the payload for GWSat and preparing it for launch.

9. Characterization of Himalayan sites for ground-based astronomy in India

During the last decade, participation in international collaborations on the Thirty Meter Telescope (TMT) and the Square Kilometre Array projects has enabled the Indian astronomy institutes as well as the industry with capabilities to design and build sub-systems for such highly sophisticated state-of-the-art telescopes. To carry forward the impetus generated by the community's direct involvement in international telescope-building projects, as well as a follow-up for the first sub-mm telescope (6-m) being built in India by SAC-ISRO, plans to build new telescopes in the optical/NIR and sub-mm wavelengths are being considered in the next 10–15 years timescale. Ground-based observations, though restricted to a few windows in which the earth's atmosphere is transparent, have always driven significant advancements by their access to sophisticated instruments and much higher duty cycle of observations compared to any space-based observatory. However, the performance of a telescope, particularly in the optical/NIR and sub-mm/mm wavelengths, depends critically on the atmospheric conditions. Thus, a necessary, if not mandatory, step in planning the new generation of ground-based telescopes in multiple wavebands is the identification of optimum locations in India for these telescopes. Evaluating a site's potential for hosting high-performance ground-based telescopes requires measuring weather parameters over extended periods (years) followed by methodical data analyses.

An effective way to reduce the influence of the atmosphere on the performance of ground-based telescopes is to select sites at high altitudes with low water vapor contents. The Himalayan high-altitude desert region of the Ladakh division in India has numerous sites with altitudes exceeding 5000–6000 m which can be explored as potential sites for building astronomical telescopes for ground-based astronomy in the optical/near-infrared and sub-mm/mm wavelengths. Identifying the sites as being suitable for the installation of highly sensitive and, hence, expensive instruments and building infrastructure at these sites currently with limited accessibility requires a rigorous two- to five-year campaign to measure virtually every atmospheric parameter that affects the performance of the telescopes. Characterization of these sites would involve the measurements of optical turbulence levels as a function of height, cloud properties and atmospheric transmission, precipitable water vapor, and meteorological parameters such as wind speed, direction, air temperature, solar radiation, and cooling rates of the ground.

In December 2022, Astronomers from IIA, RRI, and TIFR initiated a joint program to coordinate the Indian efforts towards monitoring several high altitude ($>$5000 m) Himalayan sites to evaluate their potential as sites for future optical/NIR and sub-mm telescopes. The scope of the collaboration will include setting up databases of weather data for the possible sites, installing GPS-based monitoring facilities and Automated Weather Stations to collect initial data, followed by installation of high frequency ($>$183 GHz) radiometers for more accurate estimates of water vapor at two or three of the most promising sites. The collaboration will be expanded to include the participation of all interested astronomers and also atmospheric scientists.

10. Summary

This article provides a wish list and a vision for the next 10 years on the observation facilities required for indomitable research in astronomy and astrophysics in the country. Observing facilities in India are bifurcated into high-energy ground-based, space-based, UV-Optical, IR, Submm, Radio, and gravitational wave astronomy groups to obtain an inventory list. Upgradation, developmental activities, and creation of new facilities in each of these groups, in terms of short (1–3 years), medium (3–7 years), and long-term (7–10 + years) time scales, are carefully analyzed in this article. It can be ascertained that some of the short-term tasks presented in this discussion are already being implemented or are in the pipeline. Medium-term goals are in the planning stage, and long-term goals are still a wish list. We emphasize the need for enhanced community collaboration among various institutes and universities to realize long-term projects, as these projects would require expertise that may not be limited to a single establishment. Through this article, we also wish to encourage a pressing need for discussion on long-term projects and arrive at a clear consensus on their priority. Such a consensus will help in the timely completion and production of cutting-edge research when the community proposes them for implementation. Below, we list each group's top priority projects in the long-term category.

For the high-energy ground-based facility, the MACE system, installed at Hanle, Ladakh, must be equipped with the Schwarzschild–Couder Telescope Array (STA) and the development of GRAPES-3 detectors. This would provide a capability of near-simultaneous gamma-ray observations over a wide energy range from 10^{13}–10^{19} eV. A broadband X-ray space telescope with a spectro-polarimetric instrument onboard is proposed to cover energies up to 100 KeV.

A 6–8 m class fully automated spectroscopic survey telescope with a wide field-of-view and high multiplexing capability covering UV-Optical-IR wavelength bands is proposed on high priority and to be installed quickly within the next 7–10 years. A parallel effort for building a 12–13 m class National large optical telescope (NLOT) equipped with advanced adaptive optics technology and versatile back-end instruments is among the top priority projects in the UV-Optical-IR group. Planning for a space-based 6-m UV-optical-IR should be underway in the next decade.

The eGMRT project enhances the collecting area by two-fold and the field-of-view by order of magnitude of the existing uGMRT system. The eGMRT project's realization and participation in building future SKA instruments are top priorities in the radio regime.

In the Submm regime, the development of a Submm site at altitudes greater than 5000 m is the first step in building a 15 m class Submm telescope on Indian soil equipped with instruments for observing Tera-Hertz frequencies, which forms one of the important long-term tasks.

Completion and fruitful operation of the recently sanctioned LIGO-India project will be an important milestone in the gravitational wave regime.

Realizing several of these projects requires dedicated Human Resources, state-of-the-art laboratories, and uninterrupted technological development. For this, the astronomy community also proposes laboratories that are explicitly focused on developing instruments for astronomy. The Modus operandi for such laboratories is also detailed as follows.

10.1 *New facilities, technologies, and laboratories*

10.1.1 Planetary science laboratory The solar system is our neighborhood in the universe and is accessible for detailed investigations, either for fundamental science or exploration. With several space agencies attempting deep space exploration, there is a surge in the capability to understand and utilize the available knowledge at much deeper levels than ever before. Many future planetary missions target *in-situ* observations for precise measurements to serve and enhance technological capabilities for resource utilization and maneuverability. It is inevitable at this juncture that we plan a specialized environment that can include a planetary science lab with storage facilities for extra-terrestrial materials without contamination.

The major objectives of the lab are:

1. Preparedness to receive and handle samples from internationally returned sample missions. With an established lab, we can propose specific deep-space investigations.
2. Provide experimental platforms that emulate planetary remote sensing observations.
3. Complete characterization of geological samples.
4. Generate spectral database for various geological samples in Uv-Vis-NIR-X-ray and using techniques such as XRD, Raman, Mossbauer, etc., to be used on rover platforms.
5. Determine physical properties of samples such as density, grain size, and shape.
6. Sample storage facility to store field samples in an uncontaminated environment. While the requirements for terrestrial samples (and meteorites) are not very stringent, we anticipate analyzing pristine planetary samples in the future where a controlled environment is desired. Hence, a storage facility with established procedures is needed. An exercise such as this would also help to design sample collection and holder designs for *in-situ* investigations.

10.2 *National Astronomical Instrumentation Facility (NAIF) for X-ray-to-IR astronomy*

Rationale: Astronomical instrument development differs from instrument development in other experimental physics areas in various ways. With rare exceptions, astronomical instrument development is more of an engineering implementation of well-known physics principles rather than engineering or physics research. In contrast, in a laboratory experiment in atomic physics or condensed matter physics, instrument development involves developing physics ideas. Therefore, astronomical instrument development activities often do not interest astrophysics-motivated PhD students. Moreover, pursuing astronomical observations with an instrument developed in a laboratory usually becomes possible after a long timescale, way beyond the timeframe of a PhD program. Easy access to high-quality archived data from major world observatories is another deterrent for PhD students from venturing into astronomical instrumentation in India. Attracting bright PhD and MTech students into astronomical instrumentation requires a different institutional ecosystem in which top-class astronomical instrument development is encouraged and valued without any inhibition. At institutional and national levels, there also needs to be an ecosystem that values and explicitly supports developers of competent astronomy instruments. Developing a single astronomy instrument often requires a wide range of engineering and technical expertise and various facilities, which are usually difficult to obtain in a single group/institute. At times, such knowledge and facilities become redundant if a set of astronomers retire or the research focus of an institute/group changes with time. On the other hand, a central instrument development facility can have vastly different engineering & technical expertise along with relevant facilities. In a larger and institutional setup dedicated to astronomical instrumentation, it will be possible to attract bright PhD students, maintain expertise, workforce, and facilities, and serve the needs of a wide range of instrument development.

Motto: The National Astronomical Instrumentation Facility (NAIF) should be dedicated solely to astronomical instrument development and not to supporting astronomy research by its members. This center should carry out (i) prototype instrument developments that are of interest to its faculty/engineer and (ii) in collaboration with different institutes/groups, carry out instrument development and commissioning that are of national/international importance/need.

Beyond prototype development, it should also implement projects that are needed at the national/international level and only in collaboration with astronomers at various national institutes and universities. Supporting instrument development activities at Indian universities should be a significant component of the work at NAIF.

The astronomy community needs to collaborate in upcoming technology areas via the proposed NAIF. India is already a global lead player in the development of quantum-enabled technology. The astronomy community should aim to take advantage of this development, particularly in areas such as the development of new detectors, the use of quantum clocks for networking of telescopes, the use of techniques such as light squeezing, the development of 'astrocomb' calibration systems, etc.

In a broader sense, such a center requires several facilities on campus for smooth functioning, including electronics labs, mechanical labs, optics labs, vacuum systems, clean rooms, and environmental test facilities. In addition to the above facilities, appropriate manpower will be crucial for NAIF. The staff of NAIF should include a proper number of Faculties, Engineers, Technical persons, Technicians, Administrative persons, and other maintenance and support staff.

Mode of functioning: Astronomical instrument developers from various Indian institutes/Universities can be joint faculty or associate faculty of NAIF who would lead the development activities working with engineers/technicians at NAIF. They should visit NAIF at regular intervals to work with NAIF staff. To start with, NAIF would work in this mode, and over a few years, NAIF should recruit its faculty ONLY for instrument development. Indian institutes like IIA, ARIES, etc., have successful MTech-PhD programs that churn out world-class astronomical instrumentation PhDs. NAIF can choose from such sources as their initial faculty number.

To ensure that they do not waver from its goal, NAIF faculty/engineers must not take part in astronomy research and astronomical data analysis directly, and their growth path would be determined solely by the success of the techniques/instruments they built in enabling other astronomers in frontier research. While some Indian astronomical facilities need specialized in-house instrument-building capabilities, especially for dedicated science experiments, the collaboration with NAIF and the use of the laboratory facilities will certainly enable rapid development.

NAIF should support instrument development in any wavelength band, including non-electromagnetic astronomical instruments (e.g., cosmic rays, GW, neutrino, dark matter, astrobiology, etc.). Such an institute is highly desirable and should be set up in the next 10 years.

10.3 *New technologies*

The astronomy community needs to engage in collaborations in upcoming technology areas. India is already a global lead player in the development of quantum-enabled technology. The astronomy community should aim to take advantage of this development, particularly in areas such as the development of new detectors, the use of quantum clocks for networking of telescopes, the use of techniques such as light squeezing, the development of 'astrocomb' calibration systems, etc. The development of atomic clocks to enhance their precision ensures accurate synchronization across multiple telescopes and precise time-tagging of celestial events. Globally, efforts are underway to employ AI-based technologies for optimal and efficient use of observing facilities that extract higher scientific returns from the data. The modern HPC facility is essential for addressing big data science problems in today's astronomical research. It is imperative to begin such a development in the country in collaboration with the industry sector.

As reiterated earlier, we hope this article will result in a healthy discussion on various possibilities that the Indian astronomical community can create with undeterred funding and will guide a new dawn in Indian Astronomy.

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