Summary of the SKA-India Science Case

The Square Kilometer Array (SKA) will be the world's largest and most powerful radio telescope, with an order of magnitude more sensitivity and to be built with the latest cutting edge technology. The capabilities of SKA will be phenomenal, for a wide variety of science goals and applications, and will far surpass that of any existing or planned radio astronomy facility. The SKA, once built, is expected to operate for 50 years or more. Over this large period of time, generations of researchers will use this facility. It is therefore important to develop the future human capital within the country to fully utilise the scientific and technical capability of the SKA.

India is known to have a long heritage of building radio telescopes and carrying out scientific research using them, such as the Ooty Radio Telescope, the arrays at Gauribidanur. Today, India is host to one of the most sensitive telescopes in low-frequencies, the upgraded GMRT (uGRMT), which has also been recognised as an SKA pathfinder. Indian scientists have also been extremely active in using various radio telescopes all over the world. Given such a strong background in radio astronomy within the country, Indian astronomers are ideally placed to make use of a next generation radio facility like the SKA.

In recent times, Indian scientists have been exploring possible ways to enhance their scientific contribution to the SKA, and also to build up a base of astronomers that will be prepared to use the facility when it is ready. The science initiatives in different areas are coordinated by the SKA India Science Working Groups (SWGs), somewhat in line with what is being done by the SKA Office for the international science community. These Indian SWGs have been instrumental in creating awareness related to the SKA within the Indian scientists by organising talks, workshops, meetings etc. The number of scientists interested in the SKA have grown significantly over the last few years and at present is about 150 from over 30 institutions all over the country. The Indian SWGs have not only been able to attract radio astronomers, but also astronomers working in other wave bands and theoreticians interested in model building and signal predictions. Their level of involvement with the SKA can be judged by the fact that Indian astronomers publish about 75 papers per year in peer-reviewed international journals which are related to either the SKA or one of its pathfinders. It is expected that these activities will grow significantly in the coming years and the number of people will possibly double within the next 5 to 7 years.

The capabilities of SKA Phase 1 (SKA1) will be phenomenal, for a variety of science goals and applications, and will far surpass that of any existing or planned radio astronomy facility. It will consist of two main components, namely, the SKA1-LOW to be built in Australia and SKA1-MID in South Africa The SKA1-LOW will essentially be a set of 512 “stations” each consisting of 256 log-periodic dual-polarised antenna elements. These stations will be distributed in a way that about 50% of the collecting area will be in a core of about 500 metre radius, with maximum baselines extending to about 65 kilometres. The operating frequency will be about 50-350 MHz. The SKA1-MID will consist of 133 offset Gregorian dishes of 15 metre diameter, and 64 antennas of 13.5 metre diameter from the MeerKAT (which is one of the SKA precursors). The antennas will be arranged in a compact core with a radius of about 500 metre, a further 2-dimensional array of randomly placed dishes out to 3 kilometre radius, thinning at the edges. In addition, there will be three spiral arms extending to a radius of about 80 kilometre from the centre. The SKA1-MID will initially operate at frequencies from 350 MHz to 13.8 GHz.

The goals for the SKA1 cover a wide range of research areas starting from understanding the formation of stars using hyperfine transition of neutral hydrogen, to testing Einstein's theory of general relativity using pulsars, to detailed understanding of some of the early phases in the life of the Universe. At present, the international community is busy in developing the so-called “Key Science Projects" (KSPs), i.e., large scale collaborative projects addressing key scientific questions. Keeping in line with the above, Indian astronomers too are looking to build up their science cases so that they are in positions to play significant roles in the appropriate KSPs of interest. The main science cases relevant for India have been published as scientific articles in a special issue of the *Journal of Astrophysics and Astronomy* (a journal co-published by the Indian Academy of Sciences and Astronomical Society of India in collaboration with Springer) in 2016. The issue contained 16 articles covering a wide range of science areas, almost all that are being explored by the SKA international community.

Indian astronomers, coordinated by the SKA-India Science Working Groups (SWGs), are in the process of identifying the areas where they can use SKA to carry out their research. The major areas in which different Indian SWGs are contributing towards the SKA science include

1. Cosmic dawn, reionization, cosmology.
2. Continuum surveys.
3. Transient astronomy.
4. Magnetic fields.
5. Galaxy evolution.
6. Neutron star physics.
7. Massive stars and the interstellar medium.
8. Solar, Heliospheric and Ionospheric science.

Mentioned below in brief are the activities and science goals of different SWGs:

Cosmic dawn, reionization, cosmology: The SKA provides an unique opportunity to investigate, in great detail, one of the landmark but least explored episodes of the early universe, i.e., the time when the first sources of light, e.g., the first stars/galaxies and possibly black holes were formed. The birth of these objects completely changed the way the universe evolved subsequently and is known as the cosmic dawn (CD). This is followed by the epoch of reionization (EoR) where the radiation from the first stars ionized the surrounding gas. The SKA will also help understand the nature of the mysterious dark energy at cosmic epochs never explored before. These epochs will be studied through observations of the so-called 21cm signal from atomic neutral hydrogen (HI).

The main challenge lies in extracting the extremely weak redshifted HI 21-cm signal from several orders of magnitude stronger signals from other objects in the sky (known as “foregrounds”) and subsequently interpreting the detected signal. The SKA India "EoR & Cosmology" SWG, which consists of around 60 scientists from various institutions in India, has developed adequate experiences both in theoretical modelling and observational techniques to make important contributions towards unveiling the epoch. They have been working on various theoretical aspects in order to understand and properly interpret the observed signal. They are putting in considerable effort towards understanding and detection of the signals from the Cosmic Dawn, EoR and Post Reionization era and interpret the signal to learn about the physics and the evolution of the universe. A long term observational project has also been initiated with the upgraded GMRT (uGMRT) mainly to understand the foreground contribution and various systematics associated with observations. These ongoing activities will help the group make adequate preparation for the SKA. Collectively, on the one hand, this SWG is actively involved in modelling and understanding the astrophysics of the universe and on the other hand have made several pioneering contributions to this field and have gained expertise in observations using India-based SKA-precursor the GMRT. In a nutshell, this SWG aims at the observations with SKA to achieve a better understanding of the late time evolution of the universe.

Continuum surveys: The SKA will also provide opportunities to make sensitive high resolution observations across a large range of radio frequencies. The “Continuum Survey” SWG is working on key problems in extragalactic radio astronomy, namely on active galaxies, clusters and groups of galaxies and the interplay between them using SKA by making use of this improved sensitivity. This includes, among others, understanding the physics of Active Galactic Nuclei (AGN), clusters of galaxies and cosmic web, and AGN feedback (i.e., disruptive activity driven by the AGNs) in galaxy clusters using SKA. Characterising foregrounds at high dynamic range with the uGMRT and in future with the SKA can provide an exact model for all-sky foregrounds and in turn lead to an essential foreground science with the SKA 1-LOW and SKA 1-MID telescopes. Different interesting areas of the sky (the so-called “deep fields”) are being studied in great detail using the uGMRT which will have natural overlap with SKA science. Members of this SWG are involved in addressing these problems in the light of SKA, using the skills and expertise available among the researchers in India, in collaboration with the broader international community.

Transient astronomy: With the high sensitivity and wide-field coverage of SKA, large samples of explosive transients are expected to be discovered. The “Transient Astronomy” SWG is involved in exploring this aspect using SKA. Radio wavelengths, especially in commensal survey mode, are particularly well suited for uncovering the complex transient phenomena since the observations at radio wavelengths suffer less obscuration than in other bands (e.g., optical/IR or X-rays) due to dust absorption. At the same time, multi-waveband information often provides critical source classification rapidly than possible with only radio band data. Therefore, multi-waveband observational efforts aided with detailed radio observations will be the key to the progress of transient astronomy from the middle 2020s. Radio observations of gamma ray bursts (GRBs) with SKA will not only uncover much fainter bursts and verify claims of sensitivity limited population versus intrinsically dim GRBs, they will also constrain the energetics of a large population of GRBs. At present the estimation of the rate of supernova explosions in the universe is hindered by dust obscuration in the optical band. This is expected to be lifted in the SKA era. Radio counterparts of the gravitational wave sources will be routinely detected to the Advanced LIGO sensitivity. In addition, SKA, with its wide field of view and high sensitivity, is expected to open up a new parameter space and likely to discover various new kinds of transients. SKA 1-MID is expected to increase the number of transients at least by an order of magnitude. Thus, the strength of the science case will continue to increase as more and more classes of transients are discovered with current surveys, including uGMRT, ASKAP, MWA etc. The Indian community of this SWG, given its active interest in different aspects of studies of transients, ranging from theory and modeling to ongoing and planned experiments with various radio-astronomy facilities in the country and abroad, is well poised to make a significant impact in this exciting and relatively new branch of astronomy.

Magnetic fields: The origin and evolution of magnetic fields in astrophysical objects are some of the least understood problems in astrophysics. As mentioned, SKA will have more than an order of magnitude higher sensitivity than any existing radio telescopes. This will allow the "Magnetic Field" SWG to observe magnetic fields in objects at much earlier cosmic epochs and in much greater detail. Cosmic magnetism is considered to be one of the key science cases for SKA. One of the main approaches to measure magnetic fields would be using a rotation measure grid constructed by observing the polarisation properties of background sources. This can be achieved using SKA1-MID. This survey will yield a detailed map of magnetic field distribution in our and nearby galaxies, which will help constrain the models of magnetic field amplification and maintenance in galaxies. Also, deep observations of high redshift galaxies and clusters will open a new frontier in our knowledge of the origin of magnetic fields and its time evolution. This SWG would join hands with several scientists across the world who are working on various aspects of planning such a survey. The Indian community is also involved in state-of-the-art numerical simulations to understand and interpret these measurements.

Galaxy evolution: To understand galaxy evolution through the neutral atomic hydrogen (HI) 21 cm line is one of the key drivers of SKA and hence of "Galaxy Evolution" SWG. With improved capabilities of SKA precursors and SKA it will be possible to execute large blind HI and OH spectral line surveys to address fundamental issues related to galaxy evolution and AGN activity. The key science themes that will be of interest to this SWG are: evolution of cold gas in galaxies and relationship with star formation rate density, fuelling of AGN, AGN feedback and dust-obscured AGNs, constraining space- and time-variation of fundamental constants of physics and evolution of magnetic fields in galaxies. Until the advent of an instrument like the SKA, it will not be possible to have clear and satisfactory answers to these questions related to galaxy evolution. SKA through its unprecedented sensitivity, spatial resolution and broadband coverage will make breakthrough observations in this field. It is reasonable to suggest that from the experience gained through various ongoing and upcoming efforts by this SWG and/or by using the SKA pathfinder uGMRT (for example, studies of redshifted 21 cm radiation from hydrogen), the community will be in an excellent position to take lead in these areas with SKA.

Neutron star physics: Neutron star (NS) science with the SKA will be carried out mainly through all-sky surveys with high spatial and timing resolution. As the interests of “Neutron Star” SWG correspond closely to the SKA science goals, this group envisages that the formulation and execution of relevant observational projects (in particular, those using uGMRT and AstroSat, for instance), supported by appropriate theoretical investigations is of great importance. The three major topics that can be addressed with the SKA are magnetospheric studies, equation of state and gravitational physics. The key to the puzzle of pulsar emission lies in a critical understanding of the emission region geometry through a comparison of the high time resolution pulse data and high sensitivity precision polarimetry. The sensitivity and the operating frequency range expected to be available with the SKA would allow us to undertake such investigations. This would be important in understanding the difference in emission between an ordinary pulsar and a millisecond one and would help in magnetospheric studies. The measurement of the spin-orbit coupling allows the determination of moment of inertia of a pulsar in a double pulsar system and can be done easily with the high precision timing facility expected to be available in the SKA. On the other hand, it is possible to measure a number of stellar parameters using thermonuclear bursts from LMXBs which can also be used to constrain the Equation of State. Burst properties can be studied with current and future X-ray instruments, including those of the AstroSat. These methods would be complementary to the capability of SKA to measure NS parameters. Neutron stars in binary systems have also been extremely successful in testing general relativity in the strong field , and SKA will enhance this capability significantly. The Indian community is also engaged in the attempt to detect, through pulsar timing, gravitational waves from massive spinning black hole binaries in post-Newtonian eccentric (and hyperbolic) orbits. Preliminary tests for the Indian Pulsar Timing Array (InPTA) with regular monitoring of a number of pulsars are already underway. The scope of this work would increase manifold as the SKA is likely to throw up a large number of suitable pulsar candidates for the timing array.

Massive stars and the interstellar medium: The primary motivation of “Massive Stars” SWG in the context of SKA is that high-mass stars (heavier than a few times the solar mass), with their radiative, mechanical and chemical feedback, play an important role in the dynamical and chemical evolution of the interstellar medium (ISM) and the galaxy. The outpouring of UV photons and the associated generation of ionized hydrogen (HII) regions, accompanied by strong stellar winds profoundly alter the surrounding ISM. Apart from this, massive stars evolve to become Type II Supernovae and hence inject energy and heavy elements to the ISM. However, the formation mechanism and the very early phases of evolution of this mass regime is still not well understood. The question that arises is whether the formation mechanism of high-mass stars is just a scaled up version of the low-mass regime or are the processes involved completely different. Observationally, factors that hinder the investigation of massive stars in their infancy include the rarity of sources (owing to fast evolutionary time scales), formation in clustered environment, large distances, complex, embedded and influenced environment, as well as high extinction. Hence, observational studies to probe the various phases involved in high-mass star formation and the effect they have on the surrounding ISM are of crucial importance in validating the proposed theories. In this direction, the focus of this SWG is towards understanding the early phases and the feedback of young massive stars. It is expected that with SKA, the study of massive star formation and triggering of star formation in the vicinity can be carried out by extending the current studies to scales and levels that may answer many open questions and raise new ones regarding the formation of massive stars and their interaction with the ISM.

Solar, Heliospheric and Ionospheric science: Coronal and chromospheric heating and particle acceleration by solar energetic events continue to remain the central problems in solar and space physics. The study of solar impact on the terrestrial environment, referred to as Space Weather, has steadily gained importance in the last decades. This has been a consequence of the recognition of the significant impact solar events have on our space based assets, and power and communication networks. Hence, Space Weather studies have a significant societal impact potential in addition to their scientific importance. The Solar, Heliospheric and Ionospheric (SHI) SWG includes the studies of the sun and solar phenomenon; the solar wind, the vehicle which carries the impact of the solar phenomenon to the vicinity of the Earth and beyond; and the response of the terrestrial magnetosphere and ionosphere to solar stimulus. As the solar emission is highly structured along time and frequency, a key requirement for a good solar science interferometer is its ability to capture detailed information about emission over narrow time and frequency slices. The large number of elements of the SKA1, its wide instantaneous bandwidth with good time resolution enable exactly this. In fact, the Murchison Widefield Array (MWA), a SKA-Low precursor, is already exploring previously unexplored phase space and producing very interesting science results. With its significantly improved imaging quality, angular resolution, spectral coverage and bandwidth, the SKA1 will enable the next quantum jump in the information gathering capability of the array. The Indian astronomers have been pursuing SHI science with the MWA for quite some time and are strongly interested in boosting their efforts with the SKA.

Synergies between SKA and other mega-projects: The SKA will be contemporaneous with other next-generation telescopes/facilities and there will be several science areas where SKA will add additional value to our understanding of the field. For example, the currently operating (sub-)mili-metre telescope ALMA will have synergies with the SKA in probing star-forming galaxies, molecular gas in the ISM of the galaxies and so on. Similarly, the space-based telescope, JWST, to be launched in 2021 will probe a wide range of astrophysical objects, starting from stars in our Galaxy to the distant first stars, all of which will be further enhanced by the SKA. There are plans of probing areas of the sky with future galaxy surveys like LSST and Euclid which will overlap with the SKA, allowing one to study galaxy evolution across cosmic times through multiple probes. The SKA will also have interesting synergies with X-ray missions like eXTP and Athena.

The SKA-India science community will be particularly interested in two mega-projects India is involved in, namely, the LIGO-India and TMT. Synergies between LIGO-India and SKA will involve detecting the gravitational waves using two different complementary techniques. While LIGO-India will detect the signal arising from mergers of stellar remnants (e.g., neutron stars, black holes), the SKA will enhance our understanding by using the Pulsar Timing Arrays to detect mergers of supermassive black holes. The SKA will also follow up sources detected by the ground-based detectors like LIGO-India, to study their electromagnetic counterparts. Similarly, both TMT and SKA will have lots of commonalities in science cases, starting from nearby star-forming galaxies to distant galaxies and accreting black holes.

The above science cases collectively justify that the Indian astronomy community is both strongly interested and very well prepared to explore diverse aspects of science with SKA. At present, about 150 scientists (which includes faculty members, postdoctoral fellows and PhD students) from over 30 institutions are involved in SKA-related science areas. These people are members of the SKA-India SWGs. By the time SKA1 is commissioned (around 2024), we expect the community size to grow to about 250-300.

More details on the above science cases and people involved (prepared in June 2018) can be found in http://www.ncra.tifr.res.in/ncra/skaindia/documents/ska_dpr_science_lowres.pdf. This live document will be updated periodically by the SKA-India SWG members.