Detailed Project Report on the Indian Participation in the Square Kilometre Array Megaproject: Science Justification

SKA-India Science Working Groups

June 2018

Chapter 1

Cosmic Dawn, Reionization, Cosmology with SKA - An Indian perspective

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1.1 Executive summary:

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. This provides an unique opportunity to explore, 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 i.e. stars/galaxies, black holes formed after the big bang and completely changed the way universe evolved subsequently. This event is known as the cosmic dawn (CD) and epoch of reionization (EoR). The SKA will also help understand the nature of the mysterious dark energy at redshifts never explored before. This will be done through observations of redshifted HI 21-cm 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 foreground signal and properly interpreting the detected signal. The SKA India "EoR & Cosmology" science working group which consists of $\sim$ 60 scientists from various institutes in India has adequate experiences both in theoretical modelling and observational aspects and is in position to make important contributions towards unveiling the epoch. The group has been working on various theoretical aspects in order to understand the signal and properly interpret observed signal. A long term observational project has also been initiated with the uGMRT mainly to understand the foreground contribution and various systematics associated with observations. These ongoing activities will help us taking adequate preparation for the SKA . Here we present a brief description on key science questions regarding CD/EoR/post-EoR that can addressed, the ongoing activities by the India community and plans with the SKA.

1.2 Scientific Background

One of the landmark events in the early universe is the birth of first stars, black holes. Photons emitted by these sources propagated through the intergalactic medium and completely altered its thermal and ionization state. The onset of first sources of light is often termed as **'cosmic dawn (CD)'**. Subsequent period when the neutral hydrogen (HI) was ionized is known as the **epoch of reionization (EoR)**. A small amount of HI survives even after the reionization epoch and is of great importance for probing the **post-reionization era (PEoR)**.

Hydrogen is the most abundant known constituent of the Universe. The hyperfine transition in the ground state of neutral Hydrogen gives rise to radiation 21-cm. The redshifted 21-cm line from the cosmological HI distribution appears as a background radiation in low frequency radio observations. Measurements of this redshifted 21-cm radiation holds the possibility to study the Universe over a wide redshift range starting from the dark ages through the "Cosmic Dawn" and the "Epoch of Reionization" to the present "Post-Reionization Era".

1.3 Key questions

The cosmic dawn, EoR and PEoR is often regarded as the last frontier of modern cosmology and astrophysics. On both the observational and theoretical fronts, a tremendous amount of effort has been devoted to understand these epochs. The key questions we are trying to find answers to:

1. When did first stars/galaxies, black holes appear in the universe?
2. How exactly (duration, large scale structures of HI distribution) did the reionization of HI take place ?
3. Were the first luminous sources same as we see now?
4. What is the mysterious dark energy?
5. How do galaxies evolve?

1.4 Contributions by the Indian Community

Scientists, working within India, have made several important contributions in this research area. The possibility of using the redshifted 21-cm brightness temperature fluctuations to probe the statistics of the large-scale structures in the Universe was first discussed by Bharadwaj, Nath & Sethi (2001)[2]. Bharadwaj and Ali (2004)[4] first calculated the important effect of peculiar velocities to the redshifted HI 21-cm signal, while Bharadwaj and Sethi (2001)[3], and Bharadwaj and Ali (2005)[5] showed how correlations between the visibilities measured by radio-interferometers can be used to determine the 21-cm power spectrum. Choudhury et. al. (2009)[8] was among the first few groups to develop an efficient fast code for simulating EoR redshifted HI 21-cm signal. Datta, A. et. al (2011)[15] made an important contribution by proposing that detection of redshifted HI 21-cm signal might be much easier in an "EoR Window"[1]. The work by Bagla, Khandai & Datta (2010)[17] which model HI in the PEoR Universe is also considered as an important contribution towards PEoR redshifted HI 21-cm signal predictions. Additionally, on the observational front Ali, Bharadwaj and Chengalur (2008)[21] and Ghosh et. al. (2011)[22] have presented the first observations towards quantifying the low frequency sky signal for detecting the EoR and the PEoR 21-cm power spectrum respectively. On the other hand, a group of scientists at Raman Research Institute, Bangalore is actively involved in the MWA EoR project and built a telescope suitable for detecting global CD/EoR redshifted HI 21-cm signal [23].

[1] The redshifted HI 21-cm signal is several orders of magnitude smaller compared to contributions from foreground sources. However, the foreground signal is expected to be confined in a wedge shaped region in $k_\perp - k_\parallel$ Fourier space, whereas the remaining part of the Fourier space shall remain 'clean'. Datta et al. (2010) for the first time showed that even without removing the foreground, EoR experiments can avoid the region of strong foreground contamination in ($k_\perp$, $k_\parallel$) space. This is known as EoR window.

1.5 Past/present activities and future plans with SKA

For the last two decades, Indian scientists are involved in theoretical modelling of the redshifted HI 21-cm signal and developing detection strategies and made some pioneering contributions as discussed above. In addition to that, efforts are underway by the Indian community, since the last $\sim$ 10 years towards detecting the redshifted HI 21-cm signal using the GMRT/SARAS. Activities towards observations have recently gained a considerable momentum as several young faculty members/postdocs/students having expertise in radio observations joined in the group and started a long term observational project with the uGMRT. Below we present a brief summary of the past and ongoing activities undertaken by the Indian community. We also outline future plans with SKA.

1.5.1 Cosmic dawn and Reionization science with SKA-low

Below is a detailed description of the past and ongoing CD/EoR activities and scientific quests to be pursued with the SKA by Indian scientists.

Theoretical modelling

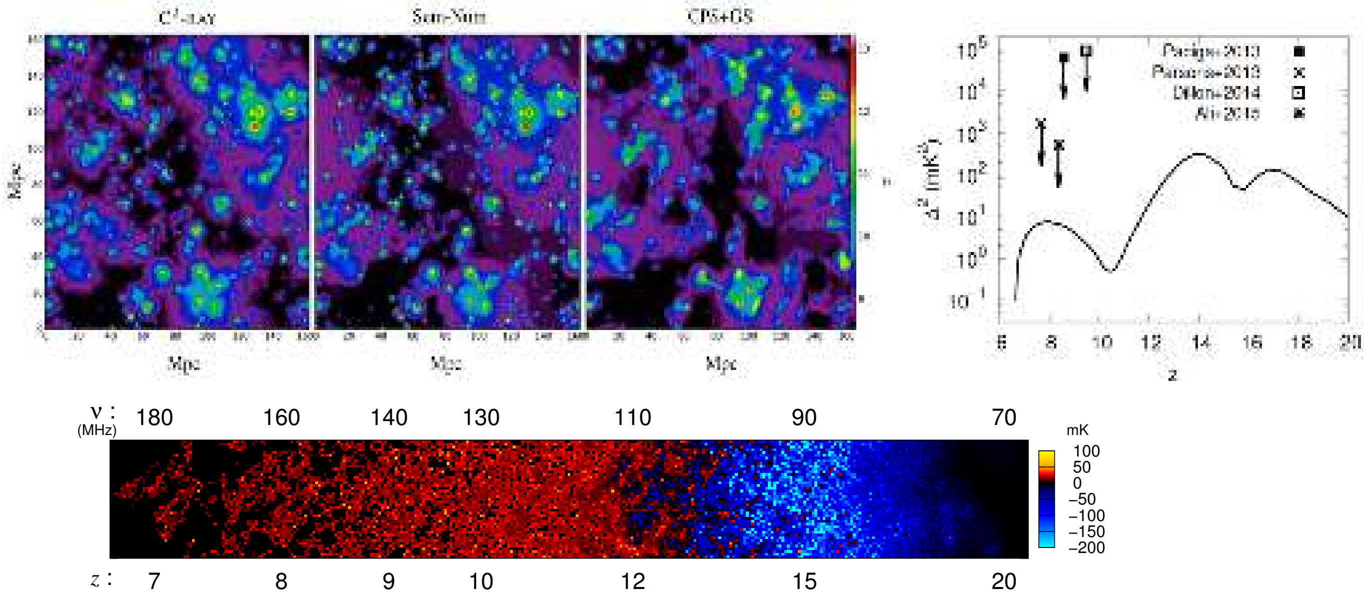

Figure 1.1: The top left panel shows the spatial distribution of the redshift of first ionization in different simulations done by the Indian scientists [35]. The top right panel, taken from Raghunath Ghara's PhD thesis, shows the current constrains on the dimensionless power spectrum from the redshifted HI 21-cm observations with various radio telescopes. The solid curve represents the dimensionless HI 21-cm power spectrum obtained from simulations (Ghara et al 2015 [9]) at scale $k = 0.1\,\mathrm{Mpc}^{-1}$ as a function of redshift.

Detailed theoretical modelling of redshifted HI 21-cm signal an important ingredient for understanding the redshifted HI 21-cm signal from CD/EoR, designing detection strategies, and extracting enormous information regarding how CD/reionization took place, the properties of the first stars and the surrounding IGM medium contained in the redshifted HI 21-cm signal. Accurate simulations with very high dynamic range are essential for these purposes. This poses a major challenge in building models of CD/EoR. Nevertheless, Indian scientists have made significant contributions in this field; Choudhury et al (2009)[8] developed one of the fast and efficient EoR simulations which has been further improved by [37, 28] (Fig. 1.1, upper panel). These simulations have been used to study the effects of redshift distortions[26], light cone effects [10, 29], non- Gaussianity and error covariance[27], bispectrum[36], prospects of detecting ionized bubbles around bright quasars[25, 10]. Ghara et al (2015)[9] has developed an efficient 1D radiative transfer algorithm to simulate redshifted HI 21-cm signal coming from CD (Fig. 1.1, lower panel) and have studied a number of important issues regarding CD HI 21-cm signal. The solid curve in the top right panel of Fig. 1 represents the dimensionless HI 21-cm power spectrum obtained from simulations (Ghara et al 2015 [9]) at scale $k = 0.1\,\mathrm{Mpc}^{-1}$ as a function of redshift.

We plan to further improve simulations already developed in order achieve better dynamic range suitable for SKA observations. We further plan to study various relevant physical effects having considerable effects on the redshifted HI 21-cm signal. This is important in order to design detection strategies and extract information contained in the signal.

Current constraints from ongoing redshifted HI 21-cm observations

The top right panel of Fig. 2 shows the current constraints on the dimensionless power spectrum from the redshifted HI 21- cm observations with various radio telescopes. Observations with the GMRT were one of the first to put a constraint on the upper limit of HI 21-cm power spectrum [61] at redshift $z = 8.6$ as $(248)^2\,\mathrm{mK}^2$ at $k = 0.5h\,\mathrm{Mpc}^{-1}$. The best upper limit on the redshifted 21-cm signal power spectrum, which comes from the PAPER experiment, is $502\,\mathrm{mK}^2$ at redshift $z = 8.4$ (Ali et al. 2015) at scales $0.15 < k < 0.5h\,\mathrm{Mpc}^{-1}$. This observation ruled out little or no heating scenario of the neutral IGM at $z = 8.4$ (Pober et al. 2015). Dillon et al. (2014) put the upper limit of $(300\mathrm{mK})^2$ at scale $k = 0.046\,\mathrm{Mpc}^{-1}$ at a little higher redshift 9.5 using the 32-tile MWA pathfinder for 22 hours of observation.

Observational strategies: Statistical Detection of the signal

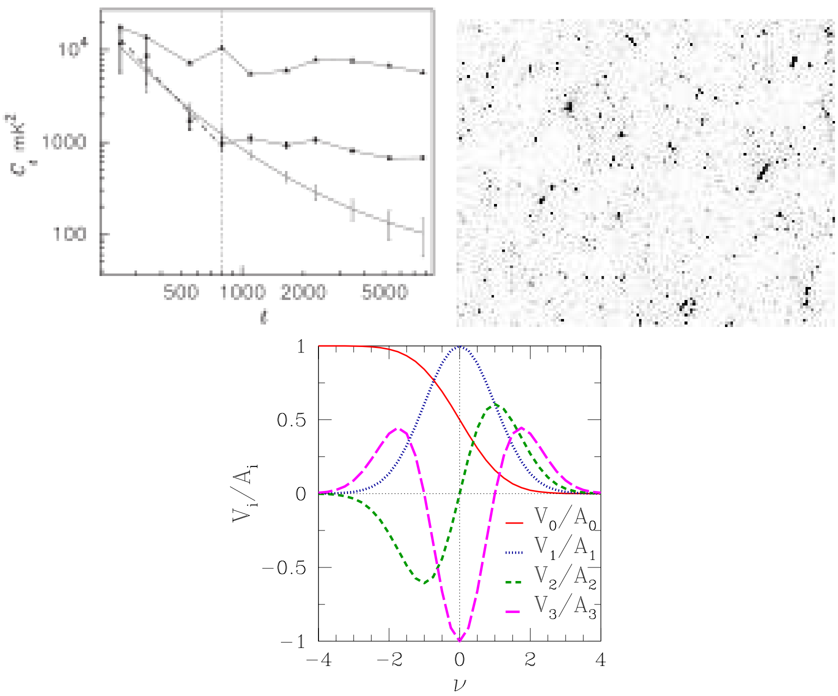

Figure 1.2: Left panel: The angular power spectrum (C_l) measurement for GMRT 150 MHz observation [18]. The triangles and the circles show results before and after subtracting the point sources respectively. The dashed line shows the best fit power law ($l \leq 800$) after removing the point sources from the data. The thin solid line (lowest curve) with $1-\sigma$ error bars shows the model prediction [21] assuming that all point sources above 20 mJy have been removed. Middle panel: A combined image from uGMRT observation for 26 hours (300-500 MHz) (Chakraborty et al. In prep.). Right panel: Various Minkowski functionals for a Gaussian field. Deviations from these shapes for the EoR fields will determine the level of non-Guassianity.

- **21-cm power spectrum:** Measurement of the power spectrum of redshifted HI 21-cm signal is one of major goals of SKA. Correlations between pairs of measured visibilities can be used to estimate the 21-cm power spectrum [3, 5]. This idea has been developed and applied to 150 MHz GMRT data in [21, 18]. The latter has resulted in one of the **first measurements of the power spectrum of the diffuse Galactic synchrotron emission (DGSE) at the frequency and angular scales relevant for the EOR signal**. Recently developed Tapered Gridded Estimator (TGE) [30, 31, 32, 34] estimates angular power spectrum directly from the interferometric visibility data, remove the noise bias self-consistently and suppresses the telescope's side-lobe response to remove the effect of un-subtracted foreground components at the outer region of the field of view. Here it is proposed to apply the TGE to SKA data to estimate the power spectrum of both the DGSE as well as the redshifted 21-cm signal from both the CD as well as the EoR.
- **21-cm bispectrum:** Owing to the patchy nature of the initial heating and reioniztion patterns, the CD and the EoR redshifted HI 21-cm signal is expected to be highly non-Gaussian [6, 27]. It should be possible to obtain significant insight into the nature of the sources which drive these process by quantifying the first order of non-Gaussianity through its bispectrum. Early analytic predictions and recent simulations [36] show that the 21-cm bispectrum is expected to be negative and is closely related to the reionization field. Here it is proposed to extend the TGE to define a bispectrum estimator through visibility triplets [6] and apply it to measure the bispectrum of the CD and EoR HI 21-cm signal using SKA data.

Analysis of HI images

The differential brightness temperature (δT_b) from the CD/EoR carries signatures of the primordial density fluctuations on sufficiently large scales. However, on small scales **Minkowski Functionals (MFs)**, which carry important information regarding HI 21-cm field (see Fig. 1.2), can be used to study non-linear gravitational evolution induced non-Gaussianity. Here the plan of the investigation is as follows: 1. Simulate the brightness temperature field with input primordial non-Gaussian perturbations. 2. Compute, analyse and identify the signatures of different non-Gaussian sources in the MFs. 3. Add instrumental noise and foregrounds expected from SKA to the simulated data and analyse the level of degrading of the sensitivity of the MFs in the presence of these effects. **Multi-fractal analysis of δT_b** distribution from CD/EoR is another way to study the statistical properties this HI distribution[42].

Bubble Detection and Individual Features

Detection of individual luminous sources (such as bright quasars, galaxies etc.) during the EoR and CD through their signatures in the redshifted HI 21-cm signal is one of the direct approaches to probe the epoch. A very efficient technique, based on matched filtering algorithm, has been developed in Datta et al (2007)[11] and is well tested with simulated data [12, 13, 14, 25, 38]. The prospect of the method was also studied for the SKA and turns out to a promising one[16]. Here it is plan to further develop this method in order to apply this to SKA data.

Foreground Modelling for SKA and removal from observed data

Astrophysical foregrounds, originating from diffuse galactic synchrotron emission (DGSE) from our own Galaxy, extragalactic point sources etc., are expected to be several orders of magnitude stronger than the redshifted HI 21-cm signal at frequencies relevant for EoR and CD studies. Successful removal of the foreground is the biggest challenge for future redshifted 21 cm observations. Various different approaches have been proposed to address the issues with foreground. The recently developed TGE by members (Choudhuri et al. 2014, 2016) in our group offers a novel technique for removal of un-subtracted point sources. We expect the TGE to reduce the 'foreground wedge' and allow us to extract the desired signal from a larger region in k-space. Recently, encouraging results are also obtained by using Neural Networks in signal estimation in presence of foreground (Choudhury et al. (in prep.)). Since the foreground component from the DGSE is partially polarized[40, 41, 43, 44, 45], the directly measured power spectrum of HI intensity fluctuation also have a significant contribution from the power spectrum of the polarized intensity in presence of even minute instrumental leakage. We are working to understand the effect of leakage in the power spectrum, methods to properly quantify the leakage of interferometers and exploring better algorithms for calibration including post liner terms in leakage.

1.5.2 Post Reionization Era: Ongoing activities and plans with SKA mid

Below is a detailed description of the past and ongoing post-EoR activities and scientific quests to be pursued with the SKA by Indian scientists.

Theoretical Modelling

It is important to model the HI distribution in the PEoR era in order to interpret the results from the upcoming observations. Semi-analytic techniques have been used to effectively model the complicated post reionization redshifted HI 21-cm signal for the intensity mapping experiments [2, 49]. Bagla et al 2010 [17] (and later [52]) first introduced this to made predictions for the direct and statistical detection of the PEoR redshifted HI 21-cm signal. Sarkar et al. [53, 54] further extended the work and simulated the HI distribution in the post-reionization era over a large range of redshifts ($z \le 6$) including the effects due to RSD over a redshift range $1 \le z \le 6$. These models offer a distinct way of estimating the cosmological parameters and/or any departure from the standard theory of structure formation [46, 48, 47] and would be used while interpreting the SKA observations from PEoR.

Observational Strategies

- **Statistical Signal Detection: 21-cm power spectrum and bispectrum:** Ghosh et. al. [22, 19] have carried out 610 MHz GMRT observations towards detecting the PEoR 21-cm power spectrum. They demonstrated that it is possible to effectively remove the foregrounds by tapering the telescope's sky response and modelling the frequency dependence of the multi-frequency angular power spectrum. Ali et. al (2006)[20] have carried out theoretical investigations on the bispectrum of the PEoR redshifted HI 21-cm signal. Here we propose to use visibility based estimation techniques [6, 19, 32] to measure the PEoR 21-cm power spectrum and bispectrum using observations from SKA-mid.

- **Cross-correlations with other tracers:** We also plan to investigate the cross correlation of the redshifted HI 21-cm signal from the PEoR with other LSS tracers, e.g, the Lyman-α forest [58, 59], Lyman-break galaxies [60] and late time anisotropies in the CMBR maps like weak lensing[57]. We have already studied the feasibility of detecting the cross-correlation signal and explored the possibility of obtaining constraints on cosmological models for the SKA-mid and found this avenue to be a highly promising one[58, 59, 60].

HI in galaxies during post EoR: Synergies with optical/infra-red surveys

A combined census of the cold HI gas and stellar components is highly important in order to understand the evolution and role of HI in galaxy formation. However, this is still not well explored during the PEoR. Recently, Dutta et al. (in preparation) has estimated HI abundance and clustering and their dependence on optical properties (like color and magnitude) for galaxies from ALFALFA survey. We plan to extend this work to infer the stellar mass, age, SFR and their interdependence to gain direct insight on the distribution of HI in the host galaxies. We also plan surveys using SKA precursors, like the uGMRT, to extend the direct observational constraints on HI at higher redshifts (Kanekar, Chengalur & Bagla in prep) and ALMA to access the distribution of the molecular gas in the HI selected galaxies. These results at lower redshifts can be used to better model the evolution of the distribution of HI in the PEoR [56]and help interpret the observations from SKA-mid.

Precision cosmology with the post EoR redshifted HI 21-cm signal

- **Cosmological Parameter Estimation:** The angular and frequency fluctuations of HI 21-cm radiation (~ 1 mK) are a very effective probe of evolution of several interesting parameters of the background cosmological model [7]. The SKA mid should be able to probe the expansion history at a precession to distinguish between different dark energy and modified gravity models and shed light on inhomogeneities in dark energy [55]. Several members in the groups are involved in devising strategies for these parameter estimations and inferring about dark energy models from the SKA mid observations of the redshifted HI .

- **Probing statistical isotropy of cosmological radio sources:** The Cosmological Principle i.e, statistical isotropy and homogeneity of the universe, can be investigated from the SKA radio continuum survey data using (1) the dipole in the spatial distribution of the radio galaxy and radio flux density, (2) degree and alignment of radio polarization, (3) anisotropy in the galaxy clustering at different scales etc. Recently, [50] have used NVSS radio catalog to search for statistical anisotropy. With ~ 10 times more sensitivity of the SKA mid, it would be possible to investigate anisotropy in the galaxy number density distribution at a very high level of precession. We plan to study the possible bias in such measurements that may arise in the continuum survey images from the instrumental effects and survey configurations using end-to-end simulations and explore algorithms to efficiently detect departures from statistical isotropy, if any, using the continuum galaxy catalogue from SKA.

1.6 Ongoing efforts with GMRT

We have been using GMRT (later uGMRT) observations mainly to understand contributions from foreground sources and study impact of various systematics. Ali et al. (2008) [21] first used GMRT 153 MHz observations and characterised the foregrounds relevant for redshifted HI 21 cm studies from the EoR. Later, Ghosh et al. (2012) [18] measured the diffuse Galactic synchrotron emission (DGSE) at an angular scale greater than $10'$ using 153 MHz GMRT observations (left panel of Fig. 2). We applied the Tapered Gridded Estimator (TGE), an estimator for efficiently measuring power spectrum (Choudhuri et al. 2014, 2016), to the real TGSS (TIFR GMRT Sky Survey) data to characterise the DGSE statistically at low frequency which is relevant for EoR studies (Choudhuri et al. 2017). Our effort with the uGMRT continues and, recently, we observed the ELAIS-N1 field at $300 - 500$ MHz using uGMRT with the aim to have better understanding of the DGSE and radio point/extended sources and various systematics that may arise due to calibration, deconvolution, point source, RFI removal etc. A continuum image for 26 hrs of observations for this field, from the above observation, is shown in the middle panel of Figure 2. Our group members are using observations with the uGMRT to understand and mitigate the issues (e.g. calibration, RFI etc [39]) that may arise for the required high dynamic range observations required for CD/EoR observations. We plan to continue our observations with the uGMRT in order to understand the foreground and various systematics as much as possible. Further, detailed polarisation studies at these frequencies of a Southern Sky field with the JVLA and the uGMRT will really be helpful as the initial calibration model for the future SKA observations. Additionally, analysis of MWA-1 datasets will give us similar initial model for calibration. We believe that experiences gained in these processes will be valuable once the SKA data becomes available.

1.7 Observations with Square Kilometer Array

- **Why do we need SKA?** The SKA would be ~ 10 times more sensitive compared to any other existing powerful radio interferometers such as LOFAR, uGMRT, MWA, PAPER. Moreover, the SKA should be able to probe redshifts up to $z \sim 20$. This will enable us to observe and study the entire CD/EoR/PEoR at large scales unlike the other existing telescopes which could go only up to redshift $z \sim 12$. Apart from that, large number of antennae, particularly at low baselines, makes it an ideal instrument for the most precise measurements of redshifted HI 21-cm signal power spectrum. The SKA is also sensitive enough for making HI 21-cm images at large scales while the present interferometers can only hope to characterise the 21cm signal from CD/EoR/PEoR in terms of statistical quantities. In addition, SKA is being built in sites which are excellent RFI-quite environment, an important aspect for making the entire project successful. The longer baselines $\sim 100\,\mathrm{km}$ and enough number of shorter baselines would provide sufficient spatial resolution to accurately model radio point sources and diffuse galactic synchrotron radiation respectively and eventually help to remove them from the observe data. Last but not the least, the cutting-edge technology along with points discussed above will enable various groundbreaking discoveries in unprecedented detail and revolutionise our understanding of early Universe.

- **SKA specifications:** Table 1.1 summarises telescope specifications for the SKA1-low and SKA1-mid. The SKA1 is a scale-downed version of the full SKA and will be built in the first phase.

Table 1.1: SKA specifications (see the SKA document 'Baseline design version 2.0' for details)

Telescopes	**Freqency Range(GHz)**	**Total antennae**	**Antenna diameter (m)**	**FoV** (deg^2)	**Cont. sensitivity** ($\mu Jy - hr^{-1/2}$)	**Maximum Baseline (km)**
SKA1-mid	0.35-14	197	15	0.49	0.75	150
SKA1-low	0.05-0.35	512	35	~ 20	3.36	80

- **Observational challenges:** The main observational challenges include:

  1. Radio Frequency Interference (RFI) mitigation
  2. Direction dependent Calibration across wide-field and wide-bandwidth.
  3. Foreground subtraction in presence of a chromatic primary beam

  The Indian community involved in observational aspects of EoR or PEoR studies are mainly using uGMRT and OWFA for the same. The group is already using state-of-the-art tools for RFI excision, Direction Dependent Calibration over smaller bandwidth. Dedicated pipelines like FLAGCAL (Chengalur et al.) is also written exclusively by Indian Community for similar work. Besides, the RRI group has also analysed and extracted EoR power spectrum from MWA-I data sets.

- **Observational strategies:** There are four major approaches to detecting redshifted HI 21-cm signal from CD/EoR/PEoR.

  1. Radio Interferometric Observations of redshifted HI 21-cm Power Spectrum
  2. Tomographic imaging of the neutral hydrogen
  3. Global Signal observations with the total power (Auto-Correlations) of SKA
  4. Observation of 21cm Forest with the SKA - similar to 21cm absorption line work with (u)GMRT

  Although the optimum observation strategy is still a subject of discussion and will largely depend on experiences gained from ongoing efforts, initial observations with the SKA telescope and our ability to calibrate the telescope systematics, a three tier observation strategy consisting of a deep, medium-deep and shallow survey has been proposed [62]. The proposed strategy will enable to achieve all goals described above. The deep survey with a total $\sim$ 5000 hrs observations with SKA1-low will enable to image structures in HI field which is not feasible with any current telescope and is unique to SKA1-low. A medium-deep survey of 50 different fields each with 100-hr integrations would cover $1,000$ sq. degrees and can be used to measure HI 21-cm power spectrum. A shallow survey of 500 fields each with 10-hr integrations would cover $10,000$ sq. degree should be able measure HI 21-cm power spectrum at larges scales inaccessible to current telescopes.

- **Anticipated results:** Highly sensitive SKA should be able to measure the redshifted HI 21 cm signal from CD/EoR/PEoR both statistically through quantities such as power spectrum, bi-spectrum etc and by making images of structures of HI. Such high precision statistical measurements and HI images are not achievable with any other existing telescopes. This will provide unprecedented details of many unknown facts such as the exact timing of CD/EoR, formation of first sources in the Universe, properties of the sources responsible for reionization, their impacts on later stages of the structure formation in the Universe etc. Direct HI imaging will provide information regarding the properties of the sources, the size distribution of the ionized regions, connection between the source population and ionized regions etc. and thus will be very useful for breaking degeneracies in reionization models. Measurement of the PEoR HI 21 cm signal with SKA-mid is a powerful and unique probe of the dark energy at redshifts $0.5 < z < 5$, a redshift range where no other tool is as efficient as the redshifted HI 21-cm signal in probing dark energy. It will be a potential probe of structures at ultra-large scales, primordial non-Gaussianity (through the HI bispectrum), precision cosmology etc.

1.8 SKA-India EoR and Cosmology science working group:

The SKA-India EoR and Cosmology science working group consists of ~ 60 students, postdocs, faculty members from ~ 25 various institutes/IITs/IISERs/NISER/Universities in India. Currently, ~ 30 faculty members are part of this group. Out of the total 60 members, ~ 20 have experiences in observations, ~ 25 have expertise in theory/statistical analysis and some are experts in both. The group is right mixture of experienced and young people which is ideal for challenging but long term project like SKA. 7 members from the group is also member of the international SKA EoR and Cosmology science group. There are ongoing and active collaborations between members of SKA India and international EoR/Cosmology groups.

1.9 Summary

This project report summarises the effort that the indian scientists are putting in towards understanding and detection of the signals from the Cosmic Dawn, EoR and Post Reionization era and interpret the signal to infer about the physics and evolution of the universe. Collectively, on the one hand, our group is actively involved in modelling and understanding the astrophysics of the universe and on the other hand have made several pioneering contribution to this field and have gained expertise in observations using india based SKA-precursor the GMRT. In a nutshell we are aiming to the observations with SKA to achieve a better understanding of the late time evolution of the universe.

Chapter 2

SKA-India DPR: Continuum Survey Science Working Group

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2.1 Executive summary

The Square Kilometer Array (SKA) will provide opportunities to make sensitive high resolution observations across a large range of radio frequencies. We describe key problems in extragalactic radio astronomy, namely on active galaxies, clusters and groups of galaxies and the interplay between them. We propose to address these problems using the skills and expertise available among the researchers in India, in collaboration with the broader international community, using the SKA.

2.2 Scientific background and the role of SKA

Active galactic nuclei (AGN) are one of the most energetic phenomena known in the Universe. They are powered by accretion of matter on to supermassive black holes that reside in the centres of all massive galaxies. Decades of research on AGN using multi-wavelength data, have helped us understand the basics of the central engines that power the large-scale outflows observed in a large fraction on them. We broadly understand what separates AGN into several sub-classes. However, when it comes to detecting "intermediate" sources between the radio-loud and radio-quiet classes, or "intermediate" sources between Fanaroff-Riley type Is (FR Is) and FR IIs, detect sources that are more than two orders of magnitude weaker than presently known, relic radio emission from previous activities of the AGN, detect giant radio jets in spiral galaxies (Figure 2.1, left-panel), observe double-double or triple-double radio galaxies, or faint ultra-steep spectrum sources at high redshifts, much higher sensitivity data than are at present available, are required. The various SKA configurations and the upcoming SKA surveys will meet these needs. Very Long Baseline Interferometry (VLBI) is required to probe the parsec-scale regions close to the central black holes. Here too, an increase in sensitivity is crucial. SKA-VLBI which will include large single antennas like the FAST radio telescope (Nan et al. 2011), will be able to study parsec and sub-parsec-scale radio jets and their magnetic field structures in both high as well as low luminosity AGN (LLAGN), the latter having remained below the sensitivity limits of the current VLBI arrays. Therefore, several urgent questions on AGN physics, the answers to which have primarily been limited by the lack of resolution, sensitivity or statistically significant number of sources, will be addressed directly by SKA.

AGN feedback provides useful constraints on large-scale structure formation in the Universe. It modifies the structure and energetics of the intra-cluster medium (ICM) and hence its understanding is crucially needed to use clusters as high precision cosmological probes. The high quality radio data expected from SKA with its higher sensitivity, high spatial and spectral resolution will aid in the calibration of cluster mass, and energy balance between cooling losses and AGN mechanical power, both in clusters and groups of galaxies. SKA will operate in the frequency range, 0.05–15 GHz with sensitivities far above those of the existing telescopes. In view of this, the galaxy-cluster science community in India have identified several key science drivers. (i) SKA will be able to detect the predicted, but not yet observed, weak radio emission from low mass merging galaxy clusters, thereby address the problems in the understanding of the role of turbulence in the ICM. The sizes of the current samples of such sources will grow more than ten-fold and help to understand the properties that govern the process of acceleration and the evolution of these phenomena to high-z. (ii) The Universe is expected to be weakly magnetised on the largest scales. SKA will probe large scale structures, e.g., the superclusters and provide direct detections of the elusive inter-galactic cosmic rays and magnetic fields. (iii) The well-known tension between the cosmological parameters estimated by state-of-the-art simulations can only be resolved by AGN studies with the SKA.

In this document, we present science interests within the continuum survey science working group and other SKA-India science working groups. We conclude by mentioning the opportunities to engage the larger scientific community in India and facilitating high-impact science using SKA with trained human-power from Indian universities. We quantify the budgetary allocation needed for training students and post-doctoral fellows in national universities, as well as presenting the research findings in suitable international fora.

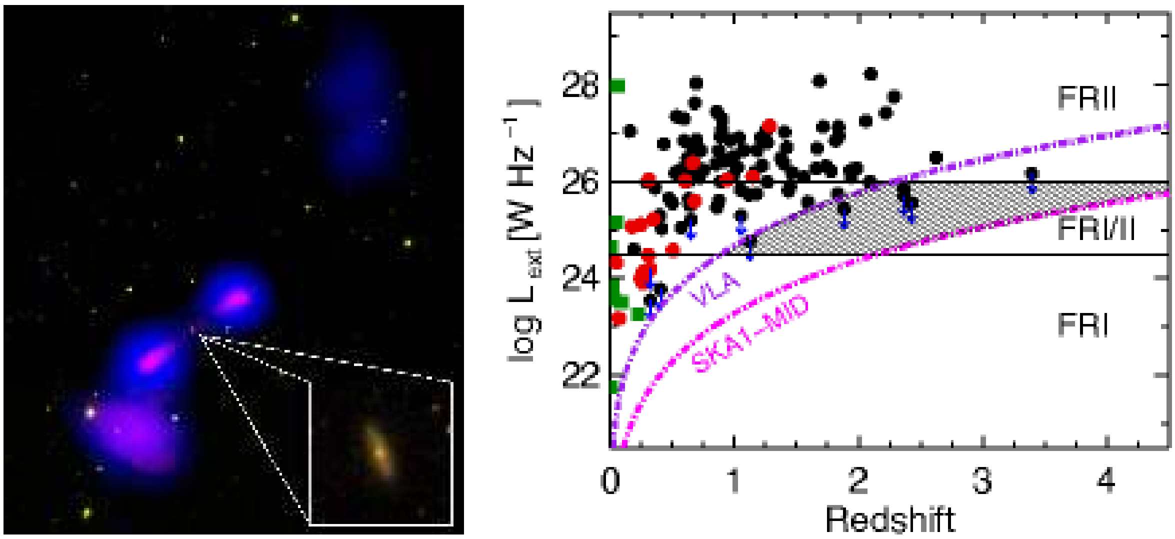

Figure 2.1: (Left) The composite image of the double-double radio galaxy, Speca; 1.4 GHz emission using VLA is in blue and 325 MHz emission using GMRT is in red. Radio emission is superimposed on the optical image from SDSS (inset zooms in on the host galaxy). (Right) 1.4 GHz extended luminosity *versus* redshift for the MOJAVE sample. Black and red circles denote quasars and BL Lac objects, respectively, while green squares denote radio galaxies. Core-only sources are represented as upper limits with downward arrows. The solid lines indicate the FR I–FR II divide (extrapolated from 178 MHz to 1.4 GHz, assuming spectral index = 0.8; $S \propto \nu^{-\alpha}$), The purple line denotes the sensitivity limit for the historical VLA which was used to carry out the MOJAVE study, while the magenta line denotes the sensitivity limit for the upcoming SKA 1–MID array (see Kharb et al. 2016 and references therein).

1. Active Galactic Nuclei

Radio-loudness, morphologies, mergers & feedback AGN are accreting supermassive black holes (SMBH; M$\sim 10^6 - 10^9$ M$_\odot$) at the centres of massive galaxies. 15−20% of AGN also produce powerful bipolar outflows (radio-loud AGN) that extend way beyond the confines of their (largely elliptical) host galaxies. While less powerful outflows are also produced in the vast majority of AGN (radio-quiet AGN), these can get stalled or disrupted due to interaction with the ISM and/or stellar winds in the largely spiral galaxies. The exact mechanisms of jet formation, collimation and propagation, are still unclear.

This has lead to urgent unresolved questions on the "radio-loud/radio-quiet dichotomy" and the "FR dichotomy" in radio-loud AGN that show jets with different morphologies. AGN activity is episodic; this can produce re-started radio outflows in the same directions (double-double radio sources, see Figure 2.1) or different directions (S-, Z- or X-shaped radio sources). Galaxy mergers, which are an essential part of galaxy evolution, can affect the radio-loudness of AGN, and lead to binary AGN. Due to bright radio emission from the bases of relativistic jets, AGN are easily visible to high redshifts (z); they can therefore probe dense galaxy environments at high-z, and the formation of SMBHs in the early Universe. AGN feedback can deeply influence the evolution of their host galaxies. Therefore, AGN studies have a powerful impact on our understanding of the Universe, and will form an integral part of SKA science.

The SKA 1–MID array has the potential to study weak radio outflows in radio-quiet AGN and diffuse lobe emission in radio-loud AGN. SKA 1–MID will be able to detect radio emission as low as 0.7 μJy beam^{-1} at 1.4 GHz (Figure 1, right panel and Kharb et al. 2016), thereby increasing the overall sensitivity by a factor of 10 to 70, compared to the current radio telescopes. It is expected that SKA will detect a much larger number of radio-"intermediate" sources, that will fill the radio-loud/radio-quiet gap. The much lower sensitivity limit of SKA 1−MID at GHz frequencies, is likely to detect nearly twice as many "intermediate" or "hybrid" FR I/FR II sources, than previous studies. SKA 1−LOW is also ideal for detecting the full extent of the diffuse lobe emission in radio-loud AGN. From estimates in Johnston-Hollitt, Dehghan & Pratley (2015), we expect the SKA surveys to detect about a few 10,000 giant radio galaxies. If we make a conservative estimate that $\sim$10% of these are in spiral hosts, we will observe a thousand new giant radio galaxies hosted by spirals. The SKA 1–MID array using band 5 (frequency range 5–14 GHz) is needed to detect closely separated binary black holes. These configurations will result in angular resolutions ranging from 0.2 arcsec to a few milli-arcseconds.

AGN hosted in dusty galaxies at high redshifts Given the order of magnitude increase in the sensitivity of the upcoming SKA surveys, we are likely to detect new classes of AGN. In particular, the radio-quiet or moderately radio-loud AGN hosted in dusty galaxies at high redshifts. In fact, the modelling of the X-ray background emission predicts a population of obscured AGN, that has not so far been detected. We can also detect the first generation radio-loud AGN at redshifts > 7. These will place stringent constraints on the relationship between black hole masses, spins, accretion rates, and production of powerful jets, as the supermassive black holes would have formed around then, in the hierarchical galaxy evolution model. Furthermore, radio AGN that are now considered outliers, like hybrid FR I/FR II sources, X-shaped or highly distorted jet sources, or "intermediate" sources that lie close to the radio-loud/radio-quiet divide (Figure 2.1, right panel), or several times re-started AGN sources, could turn out to be norm when observing the radio Universe at high sensitivity. With the detection of many more such sources, it will become possible to create their luminosity functions, and examine their evolution and redshift distributions.

Radio emission from radio-quiet AGN and star-formation SKA will contribute in explaining the much debated mechanisms responsible for the radio emission in radio-quite AGN. Thermal and non-thermal emission from the host galaxy stars and supernovae contribute to the overall radio emission in LLAGN, making it difficult/impossible to disentangle the stellar from the AGN contribution. Using SKA-mid (2-5 Band), the angular resolution of $0.4 - 0.07$ arcsec will be adequate to separate the AGN emission from star forming regions up to the $z \approx 2$. The SKA multi-frequency spectrum along with the polarimetric information will also help us in distinguishing the spectrum from different radio regions. For example, polarisation data can help us disentangle AGN jet emission from star-forming regions as the magnetic field structures are likely to more organised in AGN outflows. In addition, the improved sensitivity of SKA will help us place some constraints on the volume filling factors of the magnetic fields and relativistic plasma in both AGN and their environments.

2. Clusters of Galaxies and the Cosmic Web

Investigating cosmic-ray/particle acceleration and radio emission in cluster of galaxies In a cluster collision, how and at which stage, the energy is channeled into particle acceleration is still an open question and will only be possible with the SKA. Current observations with the (upgraded) GMRT show that cluster collisions play a major role in producing a population of cosmic ray electrons and possibly amplify magnetic fields that lead to the emission of synchrotron radiation from the ICM that are termed as radio halos and relics. The minimum power of radio halo detectable as a function of redshift is shown in Figure 2.2 (left panel) and clearly, SKA will provide the first glimpse of the properties of radio halos at $z > 0.4$ and of the “off-state”, i.e., objects that are below the sensitivity limits of GMRT (Deo & Kale 2017). Equally important is the problem of seed electron population in remnants of dead radio galaxies. A seed population of relativistic electrons is required by the re-acceleration mechanisms to overcome the inefficiency of the process and lead to detectable radio emission. Using only one case study, van Weeren et al. (2017) state that this may be injected by the radio galaxies and AGN and wide spectral imaging of radio galaxies in clusters across a wide range of redshifts using SKA will be key to solve this long-standing problem. Another equally important science driver is the radio galaxy jets and lobes, which are extended diffuse sources and can be affected by the flows of the medium surrounding them (Bagchi et al. 2006). They reflect the weather conditions of the ICM and jet dynamics, which allow us to make quantitative statements of their dynamics and energetics. Extrapolating from the detections of wide-angle and narrow-angle tailed sources, using Figure 1 of Johnston-Hollitt, Dehghan & Pratley (2015) the SKA surveys will detect $\sim 10^6$ such radio sources for a detailed statistics. Finally, about half of the known cool-core clusters in extended GMRT radio halo survey were found to host a mini-halo (Kale et al. 2016). The SKA will be sensitive to low mass, cool-core clusters as shown in Figure 2.2 and will play an important role towards building statistics.

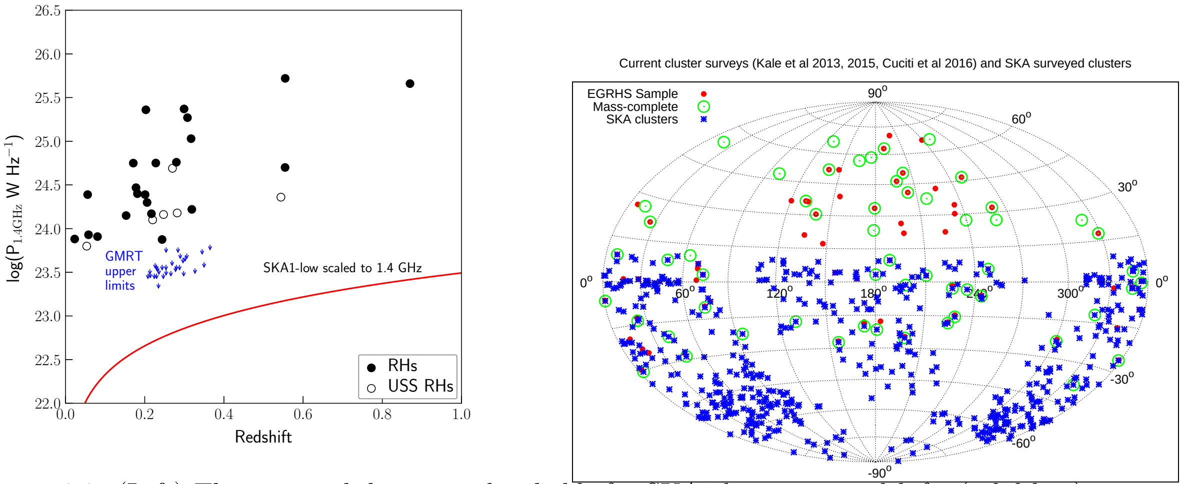

Figure 2.2: (Left) The expected detection thresholds for SKA1-low across redshifts (solid line) in comparison to the radio powers of the known radio halos and the GMRT upper limits from (Kale et al. 2016). The radio powers calculated at 158 MHz assuming an rms noise of 18 μJy beam^{-1} (according to SKA-TEL-SKO-0000818) and extrapolated to 1.4 GHz with a spectral index of 1.2 are shown. The region above the line will be explored using observations with the SKA 1–LOW. (Right) The circles show the galaxy clusters that have been observed in the targeted deep radio surveys with the GMRT. The asterisks show the clusters that are expected to be surveyed with the SKA- the sample size of surveyed clusters is expected to grow by a factor of 10.

Magnetic-field and the cosmic web: Data and simulations The growth of large scale structure is expected to produce shocks, amplify magnetic fields and is accompanied by emission of diffuse synchrotron radiation coincident with accretion shocks. Only supercluster, namely Shapley supercluster, a nearest systems ($z \sim 0.04$) have been studied in detail. Unfortunately, detection of the synchrotron web and hence the magnetic-field in it remains a challenge due to its large angular size and dynamic range. Bagchi et al. (2017) have discovered Saraswati supercluster, $z \sim$0.28 centered on extremely rich, massive ($M_{500} > 10^{15} M_\odot$) and hot ($kT_e = 8$ KeV) galaxy cluster Abell 2631. Among a handful of known superclusters, Saraswati supercluster is an ideal candidate to attempt a detection of the cosmic web. Simulations predict, flux densities of $\sim 0.12\mu$Jy, a magnetic field of ∼10–100 nG in filaments at $z \sim 0.15$ at 150 MHz (Vazza et al. 2015) assuming that primary electrons are accelerated at cosmological shock waves (Kale et al. 2016). Clearly the SKA will open the window towards detection of the cosmic web.

Cosmological simulations using computations performed with the grid-based, adaptive mesh refinement hydrodynamical code *ENZO* show that turbulence in clusters can be sustained on timescales exceeding a Gyr (Paul et al. 2011). For example, they show that an inflowing filaments towards the cluster can produce notches in the radio relics, or breaking of the shocks, usually seen as high temperature

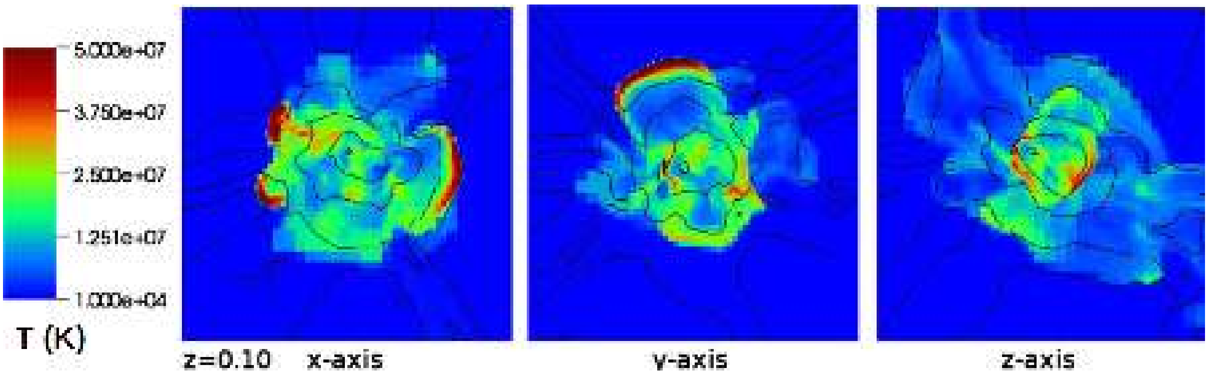

Figure 2.3: Evolution of the shock in temperature in a simulation by Paul et al. (2011), as seen from slices in three different planes of the computational volume. The panels refer to $z = 0.1$ and to slices perpendicular to the x-axis (Left), to the y-axis (Centre), and to the z-axis (Right), respectively. Each panel has a size of 7.7×7.7 Mpc h^{-1} and is cut along the center of mass of the system.

structures in the simulation (Figure 2.3). Taking this further, simulations based on the recipes for production of relativistic electrons, including magnetic field evolution along with the structure formation and radiative cooling clearly provide predictions for the radio emission from the large scale structure (see also Kale et al. 2017 and references therein). Presently these simulations are a little ahead of the data from the current facilities, e.g., the uncertainties in the efficiency of turbulent re-acceleration or the magnetic field in the large scale structure, will only be constrained by observations that will be made possible by the SKA.

3. AGN Feedback in Galaxy Clusters with SKA

Estimates of feedback energy and correlation with radio luminosity Studies of X-ray deficient cavities in clusters allow us to derive the relationship between the mechanical energy injected and radio emission of AGN jets and lobes. Such a relationship is of great interest because it can help us understand the physics of AGN jets. Owing to its high sensitivity and frequency range, SKA will also be able to trace the evolution of inflated bubbles to much larger distances in the cluster. Chaudhuri et al. (2013) have estimated the non-gravitational energy deposition profile in galaxy clusters. They found that the total energy deposition corresponding to the entropy floor is proportional to the cluster temperature (and hence cluster mass). According to their results, radio-loud AGN with luminosity 10^{23} J s^{-1} Hz^{-1} at 1.4 GHz are important for low mass clusters, with X-ray luminosity $\leq 10^{44}$ erg s^{-1}. These radio-loud AGN are also the most abundant according to the radio galaxy luminosity function. The flux density of such radio-loud AGN at $z = 0.2$ is ~ 1 mJy, and at $z = 0.5$, it is ~ 0.1 mJy. Therefore, SKA will allow us to not only have a reliable estimate of the total radio power in low mass clusters at low redshift, but will also allow us to determine their redshift evolution.

Feedback and self-similar scaling relations Observations show that there is a break in the self-similarity in galaxy clusters, with a steeper slope for low mass clusters. The simulation results for gas mass fraction as a function of cluster X-ray temperature show that AGN feedback significantly reduces the X-ray luminosities of poor clusters and groups (although temperature within r_{500} stays roughly the same) which results in a steepening of the $L_X - T$ relation on the group scale. The SKA is expected to investigate galaxy clusters using the SZ signal at $\approx 4 - 14$ GHz (SKA 1–MID) which will be useful to constrain the masses of clusters at high-z (> 1) due to its redshift independence. While the mass proxy measurements from the X-ray satellite *eROSITA* and weak lensing measurements in the Euclid survey will be limited to $z < 1$ clusters, the follow-up targeted observations from SKA 1–MID will provide mass estimates through Y–M scaling for $z > 1$ (Choudhury & Sharma 2016).

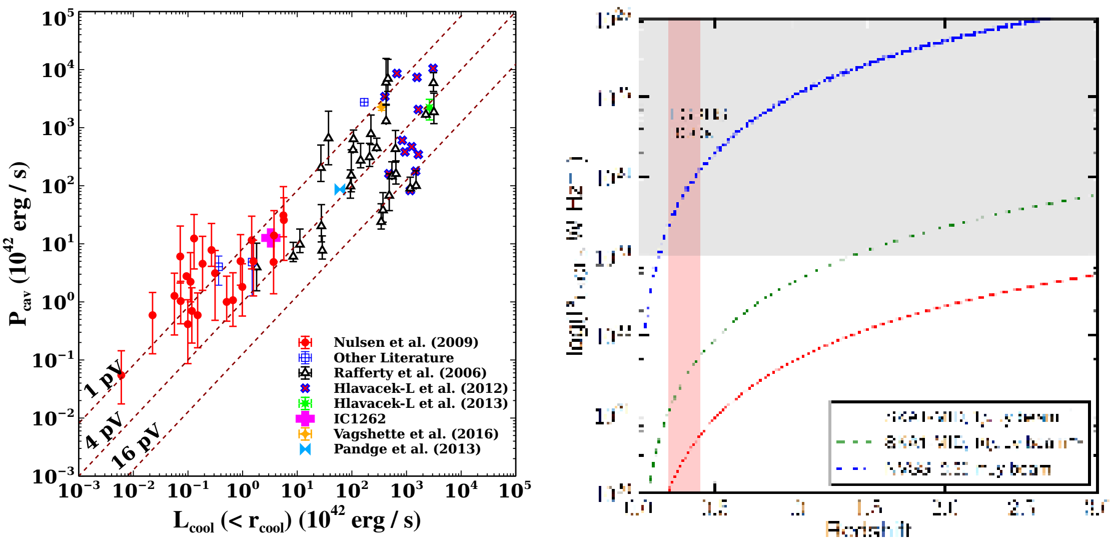

Figure 2.4: (Left) The correlation between the X-ray cavity power and X-ray cooling luminosity ($L_{\rm cool}$) for the sample of groups. The diagonal lines represent samples where $P_{\rm cav} = L_{\rm ICM}$ assuming pV, $4pV$, $16pV$ as the total enthalpy of the cavities (Private communication M. Pandge.) (Right) The radio power at 1.4 GHz versus redshift for the detection thresholds of the NRAO VLA sky survey and SKA 1−MID. The extended GMRT radio halo survey sample of bright cluster galaxies is limited to the redshift range of 0.2−0.4 shown by the vertical shaded band. The grey shaded region shows the typical range of radio powers of bright cluster galaxies (see also Kale et al. 2016).

2.3 Synergy of Continuum Survey Science with Science from other Science Working Groups

Cosmology, epoch of reionisation and magnetism science working groups Detection of the highly redshifted 21 cm "spin-flip" transition of the neutral Hydrogen against the cosmic microwave background (CMB) is considered as a promising probe for the cosmic dark ages (z > 30 or ν < 45 MHz), the Cosmic Dawn ($30 > z > 15$ or 45 MHz $< \nu <$ 90 MHz), the epoch of reionisation ($15 > z > 6$ or 90 MHz $< \nu <$ 200 MHz), and the post reionisation epoch ($z < 6$). Accuracy of the extraction of the both the global 21 cm signal as well as the redshifted 21 cm fluctuations strongly depends on the ability to characterise and remove the foregrounds from the data. Although there are several techniques used to deal with the foregrounds, subtraction of foreground accurately is a challenge due to multiple reasons (see Roy Choudhury et al. 2016). Characterising foregrounds at high dynamic range with the upgraded GMRT, an SKA pathfinder instrument 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.

2.4 Human Resource Development

Among 33 proposers, who had also contributed to the SKA-India science case book, ∼70% are permanent faculty staff members, ∼80% have led an observing proposal for the upgraded GMRT as a P.I and are well versed with the strengths of upgraded GMRT or the Jansky-VLA. The proposers have aimed to address a variety of challenging science drivers and several of the science drivers are listed in this DPR. The team members also have expertise in handling large data, have performed data reduction and analyses, undertook simulations when needed, etc. Several team members are presently working actively to make available a data reduction pipeline for the upgraded GMRT data. We believe that there could be a few more, ∼20% who are not part of the science working group but could contribute to the project in the long run.

Citizen scientists utilising publicly available data from observatories have been able to investigate morphological identification of massive spiral galaxies hosting radio-loud AGN in the GMRT TIFR−GMRT sky survey imaging. Some of the RAD@home (Hota et al. 2014, 2016) volunteers have co-authored GMRT observing proposals, and clearly there is a need to engage citizens in ever-more advanced analyses. These volunteers contribute in various ways: visually classifying features in images and light curves, exploring models constrained by astronomical data sets, and initiating new scientific inquiries. Citizen scientists (i) have published as first authors in research journals, (ii) are able to devote their attentions to whatever topics interest them, and (iii) ask unusual questions and make connections and suggestions that professional scientists have completely missed (Marshall et al. 2015). Hence, this is an area of great potential, i.e., the role the citizen astronomers would play in order to further exploit not only the continuum survey data products, but also a variety of other data products using the SKA.

Chapter 3

Detailed Project Report - SKA India Transient SWG: Probing extreme phenomena - Transient Astronomy with SKA and its Precursors

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3.1 Executive Summary

With the high sensitivity and wide-field coverage of the Square Kilometre Array (SKA), large samples of explosive transients are expected to be discovered. 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, multiwaveband information often provides critical source classification rapidly than possible with only radio band data. Therefore, multiwaveband observational efforts aided with detailed radio observations will be the key to progress of transients astronomy from the middle 2020s. Radio observations of gamma ray bursts (GRBs) with SKA will not only uncover much fainter bursts and verifying claims of sensitivity limited population versus intrinsically dim GRBs, they will also constraint energetics of a large population of GRBs. The supernova rate problem caused by dust extinction in optical bands is expected to be lifted in the SKA era. Radio counterparts of the gravitational waves will be routinely detected to the Advanced LIGO sensitivity. Other fields of transient astronomy 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.

3.2 Scientific background

Transient phenomenon usually represent extremes of gravitational and magnetic fields, velocity, temperature, pressure and density. Exploration of transient phenomena is an exciting and rapidly growing area of radio astronomy. Transient radio sources are compact sources and are locations of explosive or dynamic events. In terms of duration, radio transients phenomenon can be classified into two classes, long time variability (min-days) and bursting radio sky (msec-sec, Carilli 2014). They are dominated by three kinds of emission mechanisms in radio bands:

1:) **Incoherent synchrotron emission:** Transients with incoherent emission show relatively slow variability, and are limited by brightness temperature. These events are mainly associated with explosive events, such as Gamma Ray Bursts (GRBs), supernovae (SNe), X-ray binaries (XRBs), tidal disruption events (TDE), Active Galactic Nuclei (AGN) etc.

2:) **Non-thermal coherent emission**: Transients associated with coherent emission show relatively fast variability, high brightness temperature and often show high polarization associated with them, such as Fast Radio bursts (FRBs), pulsars, flare stars etc.
3:) **Thermal emission**: These kind of emission is seen in slow transients, novae and symbiotic stars.

Various transient phenomenon and their time scales are plotted in Fig. 3.1. SKA holds great potential to revolutionize the Transient Astronomy, thereby opening up incredible new science avenues in astrophysics.

3.3 Indian Contributions

In India active research is going on in transient astronomy, especially in the fields of SNe, GRBs, Pulsars, novae, X-ray binaries, and electromagnetic (EM) signatures in gravitational wave (GW) sources. Major observational facilities operated by NCRA, ARIES, IIA etc. are widely used. Researchers also avail the wealth of archival data from high energy space missions like *RXTE*, *XMM-Newton*, *Swift*, *Chandra* and *Fermi*. Indian Astronomers have access to several observational facilities, both presently existing and to come in the future.

In terms of specific contributions, Bera et al (2016) have developed a general formalism for FRB detection by any radio telescope, and have shown that the detection rate of FRBs at low frequencies can be quite appreciable. In particular, constraints on the value of the spectral index for FRBs can best be obtained by such low frequency observations. There is also an ongoing program to develop a dedicated pipeline at the GMRT, for real-time detection of fast transients. This pipeline is intended to run both as a stand-alone program as well as in piggyback mode simultaneously with other, possibly imaging, observations at the observatory. The concept for this pipeline, outlined in Bhat et al (2013), is particularly well suited to multi-element telescopes like the GMRT, and will be easily extendable to the SKA mid. This provides synergy with the Neutron Star SWG as FRBs are going to be bi-products in the Pulsar surveys. We are closely working with them.

Avinash Deshpande, has proposed a broadband Indian Sky Watch Array Network (SWAN). This is a proposed competitive coordinated network (40+ stations across India) with nominally 1000 sq. m. array area at each location and operation spanning a decade in frequency: 50 to 500 MHz. The main objective is to facilitate and conduct searches and studies of fast (typically of sub-second duration) and slow transient radio radiation originating from astronomical sources. The proposed Indian-SWAN is optimized to search for a large volume of the space with required sensitivity to detect FRB signals routinely, enabling a proper, detailed study to be carried out.

In addition, H. A. Aswathappa and Avinash Deshpande have conducted a sky survey at 35 MHz using the Gauribidanur telescope, covering the full visible sky, providing data on 3000 fields observed for 20 minutes each, with raw voltages recorded across a 1 MHz bandwidth. Some of these data have also been used to search for radio counterparts of the FERMI-LAT sources (Maan, Aswathappa and Deshpande, 2012; Maan and Aswathappa, 2014).

The above initiatives, driven by the strong interest and skill sets of the Indian astronomy community in the area of transients, combined with an exciting set of ongoing activities and plans that would involve a much wider participation from the younger generations, provide the desired setting to build up the group's active participation in the SKA.

3.4 Scientific Justification

In this section we summarize the main forefront issues in various fields of Transient Astronomy, current efforts and role of SKA.

3.4.1 Gamma Ray Bursts

Unsolved problems: GRBs are one of the farthest known objects so far, with the redshift distribution ranging from 0.008 to ~ 9. We currently understand them as catastrophic events generating a central engine which launches an ultra-relativistic collimated outflow, and an afterglow due to interaction of the jet with the surrounding media, which shows its presence in various electromagnetic (EM) bands. While our knowledge about GRBs have definitely enhanced, the very nature of the progenitor, and the

radiation physics giving rise to the observed emission in both prompt as well afterglow phase is yet to be solved. Some of the prominent questions that need to be answered are: what are the microphysics involved in these radiation events?; what are the dynamics of the outflow resulting in these variable light curves?; GRB are believed to be collimated jet emissions to reconcile with the observed energetics, however, why jet breaks are not observed in all afterglow observations?; True budget for GRB energetics?
Current efforts and role of SKA: Afterglow emission has always been instrumental in diagnosing burst physics like the energy in the explosion, structure of jet, nature of the ambient medium and the physics of relativistic shocks. Late time low frequency observations are especially been useful to constrain the GRB energetics independent of the jet geometry. However, only handful of GRBs have been detected at late times. There has been revolution in the field of GRBs afterglows with several dedicated instruments. While in the *Swift* era, almost 93% of GRBs have a detected X-ray afterglow, only 31% have radio afterglows.The SKA, with its extreme sensitivity, will dramatically improve statistics of radio afterglows. Using numerical simulation of the forward shock, Burlon et al. (2015) predicts around $400-500$ sr^{-1} yr^{-1} radio afterglows in SKA-1 MID bands. In addition, radio afterglow monitoring campaigns in higher SKA bands will definitely be useful in exploring reverse shock characteristics, where Indian scientists have proven expertize. SKA-1 MID will be able to detect a bright radio flare like GRB990123 even if it happens at a redshift of ~ 10.

3.4.2 Supernovae

Unsolved problems: Supernovae (SNe) are explosive events with two basic types: 1. thermonuclear Supernovae (SNe-Ia), caused by the explosion of a massive white dwarf in a binary system. 2. Core-Collapse Supernovae (CCSNe), which mark the end of the life of massive stars. SNe are most complex in terms of stellar evolution. They encompass objects of different stellar evolution and mass loss history (Chandra et. al 2015). A challenging problem in SNe IIn is that neither their evolutionary status, nor the origin of the tremendous mass loss rates of their pre-SN progenitor stars is known. Radio lightcurves are crucial to understand the history of the progenitor star. The physical processes driving the radio emission, and its temporal and spectral properties, turns out to be not only a characteristic of these explosive events itself, but of the pre-explosive evolutionary history of their precursor (progenitor) as well. However, currently only $\sim 10\%$ of the discovered core-collapse SNe show radio emission. There is also a discrepancy between star formation rate and SNe explosion rate.
Current efforts and role of SKA: Tremendous amount of SN research is going on in India by various groups, in multiwavebands including GMRT, HST, Devasthal etc., and open sky NASA based telescopes. GMRT and VLA are instrumental in carrying out detailed studies of SNe but only the radio-brightest SNe are detected, and systematic searches of radio emission from core-collapse supernovae (CCSNe) are still lacking. Optically dim SNe are missing due to dust obscuration in the host. Therefore, finding SNe in radio bands are more promising to avoid dust obscuration and determine the true SN rate and thus get a handle on star formation rate. The low frequency models have revealed SKA, with an expected sensitivity ten times that of SKA-1, is expected to detect CCSNe in the local Universe by the thousands (Wang et al. 2015). Therefore, commensal SKA observations could potentially discover all CCSNe in the local universe, thus yielding an accurate determination of the volumetric CCSN rate. SKA will also be contemporaneous with LSST and WISE, thus opening a radio vista in to the statistical properties of a dynamic universe, while as a follow-up instrument, its high sensitivity and resolution will answer several crucial questions about the nature and origins of various SNe, both in the early and in the present Universe. With an improved sensitivity level of 1 μJy, one can detect the brightest of radio SNe, such as the Type IIn SN 1988Z up to redshift of z=1.

3.4.3 Gravitational Wave Counterparts

Unsolved problems: Binary black-hole (BBH) mergers are routinely discovered by the Advanced LIGO and VIRGO gravitational wave detectors starting from the first BBH detection in 2015 (Abott et al. 2016a) The era of multi-messenger astronomy began with the joint detection of the binary neutron star merger by gravitational wave and electromagnetic observatories (Abott et al. 2017a, 2017b). It has been long realized that the EM follow ups of GW events (involving merger of at least one neutron star) will be able to unravel many long standing puzzles in Astronomy, such as: a) the nature of short gamma-ray bursts (e.g. Narayan et al. 1992; Rezzolla et al. 2011) b) r-process nucleosynthesis at the merger site (e.g. Rosswog et al. 2014; van de Voort et al. 2015), c) probing the expansion history of the universe (Nissanke et al., 2010).

Current efforts and role of SKA: The radio follow up of GW170817 has revealed new insights into the physics of GRBs and mergers, and have indicated that the emission could be coming from the cocoon powered by the quenched jet, or the narrowly beamed structured jet. The uGMRT detected the lowest frequency emission from the merger event (Mooley et al. 2017, Resmi et al., 2018). One of the interesting prospects of SKA for multi-messenger astronomy lies in the radio follow up of GW triggers from the IInd and IIIrd generation GW detectors that may be operational at the time of SKA. Assuming a five detector network of advanced GW detectors, Saleem et al. (2017) calculated the rate of potential radio afterglow detections by JVLA in 5 GHz to be $0.04 - 47$ per year, for a merger rate of $0.6 - 774$ per Gpc^3 per yr (Dominik et al. 2012), provided all mergers are associated with standard relativistic jets. With the higher sensitivity of SKA1 mid bands, SKA is likely to detect all GW mergers within Advanced LIGO sensitivity. It is interesting to note that SKA will be one of the unique instruments which by itself will be searching for GWs (from supermassive BH binaries) in the pulsar timing array mode and also looking for EM counterparts to ground-based GW detector triggers. Hence multi-messenger astronomy associated with these systems is going to be very exciting. India having a very large involvement in GW science and its EM counterparts is very well placed for this.

3.4.4 Fast Radio Bursts

Unsolved problems: FRBs are perhaps the most exciting variety of transient events, and also the most difficult to observe and localise in the sky. They probe high brightness temperature emission, likely associated with extreme states of matter. They are also powerful probes of intervening media owing to dispersion, scattering and Faraday rotation. FRBs are characterised by their short durations (millisecond) and high values of the dispersion measure (DM, $\geq 400 - 1600$,Thornton et al. 2013). Because of the large values of DM associated with them, , $5 - 20$ times larger than the DM value for the Milky way, FRBs are believed to be of extragalactic origin. The understanding of the physical origin of FRBs remains as an open challenge. Detection of repeating bursts from FRB 121102 (Spitler et al, 2016) argues against catastrophic models, at least for this event. However, the possibility of multiple types of populations of FRBs (based on their origin) can not be ruled out. In order to improve our understanding of the nature and origin of FRBs, and to use them as effective probes of interesting physics, it is important to increase the sample size by a significant amount.

Current efforts and role of SKA: This was confirmed by the detection of the associated galaxy at $z = 0.19$ for FRB121102 (Chatterjee16). GMRT has been involved in FRB searches in conjunction with Parkes. A pipeline is being developed to search for FRBs in pulsar survey data. The detection and localization of thousands of FRBs at cosmological distances will directly locate the missing baryons in intergalactic space that constitute at least 50% of the present-day Universe's baryonic content and determine their association with galaxy and cluster halos. As cosmological rulers, these bursts measure the curvature of the Universe and can help determine the dark energy equation of state at redshifts ≥ 2. The SKA can achieve all of this with a design that has a wide field of view, a substantial fraction of its collecting area in a compact configuration (80% within a 3 km radius), and a capacity to process high time resolution (1 ms) signals. SKA1 Low and SKA1 Mid will both be extremely instrumental for high precision cosmology with FRBs.

3.4.5 Stellar to supermassive black holes

Unsolved problems: Spinning accreting black holes are currently understood to be the prime candidates for the production of bipolar, synchrotron-emitting, often relativistic jets that have been seen over a very large range of physical scales. Accreting black holes are highly variable emitters at a variety of frequencies and time-scales. There is strong coupling between the accretion processes that lead to a stellar mass black hole (SMBH) forming an active galactic nucleus (AGN) on the one hand and star formation in their host galaxies on the other. Understanding these scaling relationships are beacons to cosmic evolution. However, our physical understanding of the accretion process, jet launch and feedback, has remained sketchy. In addition, while accreting supermassive black holes are abundant and cover a large range of power, known SMBH are few, but produce jets that have dynamical time-scales within our observing windows that can be monitored with high resolution in physical scale.

Current efforts and role of SKA: Time-domain studies are the main channels to probe the neighbourhood of black holes ranging from stellar mass black holes all the way to supermassive blackholes. Radio observations probe the spatial domain when the variability is on small spatial scales. In V404 Cygni, GMRT measurements have revealed synchrotron self-absorbed optically thick radio jet, which allowed us to infer infer the jet size, magnetic field, minimum total energy, and transient jet power (Chandra & Kanekar 2017). The relatively low value of the jet power, despite V404 Cygni's high black hole spin parameter, suggested that the radio jet power does not correlate with the spin parameter. SKA will be able to enormously increase the number of stellar-mass black hole candidates from the currently known dozen or so that are confined to the Milky Way, and probe both the weak radio phases and the relativistic ejection phases of accreting stellar black holes. SKA's synoptic imaging capability coupled with its sensitivity offers a way to find these systems in regions of their parameter space not sampled before, , and probe both the weak radio phases and the relativistic ejection phases of accreting stellar black holes.

3.4.6 Novae Outbursts:

Unsolved problems: A nova outburst is triggered by runaway thermonuclear burning on the surface of an accreting white dwarf in an interacting binary system. Nova systems serve as valuable astrophysical laboratories in the studies of physics of accretion onto compact, evolved objects, and thermonuclear runaways on semi-degenerate surface which give insight into nuclear reaction networks. However, despite their astrophysical significance as nearby laboratories, aspects of these relatively common stellar explosions remain poorly understood.
Current efforts and role of SKA: Although much of our current understanding of these systems has come from the optical observations, multi-waveband observations have augmented and enhanced our understanding. The primary mechanism of radio emission is thermal bremsstrahlung from the warm ejecta. In addition, in the case of novae in dense environment, the interaction of the nova ejecta with the environment gives rise to a shock, which in turn may give rise to a non-thermal, synchrotron emission component. Previous radio observations of nova outbursts have illustrated the unique insights into nova explosions these observations bring. SKA and its precursors will be very well placed to study novae at various epochs of the outburst. While the thermal emission from most novae have been well observed in the higher (> 1 GHz) frequencies, the sensitivities of the existing facilities are not well suited to detect thermal emission at < 1 GHz. The improved sensitivity of SKA at the lower frequencies will enable detection of the thermal emission at these frequencies, providing a better understanding of the evolution of the physical conditions in the nova ejecta. Also, the < 1 GHz frequencies are ideal to observe the non-thermal emission from novae, especially from the recurrent nova systems (Kantharia et al. 2016).

3.5 Why SKA?

While X-ray and optical afterglows stay above detection limits only for weeks or months, radio afterglows of nearby bursts can be detected upto years (Frail et al. 1999, Resmi et al. 2005). GMRT and uGMRT have detected several GRBs at late times (Nayana & Chandra 2016, Chandra 2017). The longevity of radio afterglows make them unique laboratories to study the dynamics and evolution of relativistic shocks. Fireball transition into non-relativistic regime can be probed through low frequency radio bands (Frail et al. 1999, van der Horst et al. 2007) This regime is largely unexplored due to limited number of bursts in past that stayed above detection limit beyond sub-relativistic regime. SKA with its μJy level sensitivity will be able to extend the afterglow follow up time scale. This will provide us with an unprecedented opportunity to study the deep non-relativistic regime of afterglow dynamics and thereby will be able to refine our understanding of relativistic to non-relativistic transition and energetics of the GRBs. (Burlon et al. 2015) have computed the rate of detectable GRB afterglows in non-relativistic regime to be about 25% with full SKA.

SKA, with an expected sensitivity ten times that of SKA-1, is expected to detect CCSNe by the thousands (Wang et al. 2015). Therefore, commensal SKA observations could potentially discover all CCSNe in the local universe, thus yielding an accurate determination of the volumetric CCSN rate. SKA will also be contemporaneous with LSST and WISE, thus opening a radio vista in to the statistical properties of a dynamic universe, while as a follow-up instrument, its high sensitivity and resolution will answer several crucial questions about the nature and origins of various SNe, both in the early and in the present Universe.

Despite their great cosmological importance, the exact nature of progenitors of SN-Ia remains unknown. There is controversy between single degenerate and double degenerate models. To date, no SNe-Ia has been detected in the radio. Though this could also be a selection effect since only a few bright SNe-Ia have been followed up in the radio band immediately post-shock, and because a less massive and/or dense CSM would mean that the radio flux density would lie below the detection threshold of the current generation of radio telescopes. Thus, for nearby type-Ia SNe ($\simeq 2$ such events are detected each year at $V_{peak} < 13$), even a non-detection of radio emission in the SKA bands would set tight constraints on the mass loss history of the progenitor system, and hence on the theoretical model. It is also to be noted that SNe of all kinds, whose optical emission is shrouded by dust, would nevertheless be visible in the SKA bands.

3.6 Results and conclusion

The dynamic radio sky remains poorly sampled as compared to sky in X-ray and γ-ray bands. This is because currently it is difficult to obtain both high time resolution and wide FoVs simultaneously. This is where the SKA, with its wide FoV and high sensitivity, is expected to open up a new parameter space in the search for radio transients. The SKA will be a premier instrument for transient science. SKA is expected to increase number of transients at least by an order of magnitude. In optical bands, LSST, which will be contemporary of SKA, anticipates finding around 1 million transients per night. However, this rate is not known at the GHz bands. But it is estimated that around 1% of the mJy sources are variable (Frail et al. 2012). They claim that with 10 μJy rms, one can expect around one transient per degree. This is achievable by SKA-1 MID. Not only will these new discoveries trace out well-populated areas of phase space of explosions see Fig. 3.1, but quite likely, they will provide hitherto unknown linkages that will clarify or strengthen suspected unity among diversity (Pietka et al. 2015).

This strength of the science case will continue to increase as more and more class of transients are discovered with current surveys, including uGMRT, ASKAP, MWA etc. There is much development going on in hardware, software, simulation and data analysis techniques, all to improve the chances of detecting transients. All of the next generation telescopes are including the transient science case as one of the core goals, and this is also being reflected in developments at nearly all other wavelengths.

Indian Participation: Currently more than two dozen faculty members in various institutes in India are involved in transient Astronomy, with ~ 15 actively participating in SKA. The Indian community, given its active interests in different aspects of studies of transients, ranging from theory & modeling to ongoing & 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.

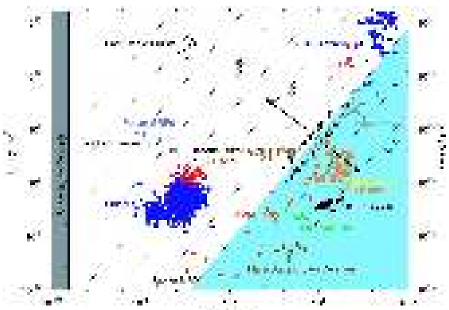

Figure 3.1: Parameter space for transient sources. One can identify the sources of coherent radio emission for comparison with the more slowly varying synchrotron transients (reproduced from Pietka et al. 2015).

Chapter 4

Detailed Project Report - Probing magnetic fields with SKA and its precursors

S. Roy, S. Sur, K. Subramanian, A. Mangalam, S. Paul, P. Dutta, T. R. Seshadri, H. Chand

4.1 Executive Summary

Origin and evolution of magnetic fields in astrophysical objects have remained one of the unsettled problems in astrophysics. The upcoming Square Kilometre Array (SKA) will have more than an order of magnitude higher sensitivity than any existing radio telescopes. This will allow to observe magnetic fields in objects at much larger distance (redshift) and with much greater details. Cosmic magnetism is considered to be one of the key science cases for the upcoming SKA. Here we present some of the contributions and present capabilities of the Indian astronomers interested in this field, and discuss some of the science cases they would like to pursue with the SKA and its precursors.

4.2 Scientific Background

Magnetic fields are present in almost every astrophysical object with varying field strengths and degree of coherence. Understanding their origin and evolution, apart from being an exciting intellectual challenge in its own right, is also crucial as they dynamically influence many astrophysical phenomena. These include both primordial and contemporary star formation, multiphase structure of the interstellar medium (ISM), propagation and confinement of cosmic rays, viscosity and thermal conductivity in the intracluster medium (ICM) and launching of jets from accretion disks formed around black holes.

The advent of the Square Kilometre Array (SKA) will provide important insights about the strength and structure of magnetic fields in galaxies and clusters and the interplay between magnetic fields, multiphase gas and star formation. Indeed, the 'Origin of Cosmic Magnetism' is one of the dominant themes of research of the SKA. In light of these impending observational progress we discuss several science cases which are of interest to the Indian community working in the field of magnetic fields and astrophysical turbulence. A detailed account of these science cases has been published earlier in Roy et al. [149].

4.3 Contributions by the Indian community

At the national level, a number of people across different institutions have made important contributions over a wide range of issues in cosmic magnetism. The research work pursued by these different groups can be broadly categorised under the following heads :

- Addressing core theoretical issues associated with turbulent dynamos in galaxies and clusters [118, 117, 115]. Considerable effort has also been undertaken to probe observational signatures of primordial magnetic fields in the cosmic microwave background (CMB) radiation [150, 153, and references therein].
- Applying the theoretical knowledge of dynamos to probe fields in galaxies and clusters using numerical simulations of the interstellar medium (ISM) in galaxies and the intracluster medium (ICM) in clusters with the purpose of drawing comparisons with observations [155, 114, 157].
- One of the most influential theory for magnetohydrodynamical (MHD) turbulence was proposed [128].
- Probing magnetic fields through Faraday rotation in the central region of Milky Way [148, 147].
- Equipartition magnetic fields have been studied as a function of galactocentric radius in nearby spiral galaxies [109] (see Fig. 1 as an example).

4.4 Unsolved/Outstanding science problems

Some of the outstanding science questions that we plan to address with SKA are :

1. How are magnetic fields generated in young galaxies? How do they then evolve in redshift along with the host galaxy? What is the role of magnetic fields in the evolution of discrete objects in the host galaxy?
2. What is the strength and distribution of magnetic fields in galaxy clusters & the cosmic web?
3. What is the degree of coherence of random magnetic fields generated by turbulent flows in high magnetic Prandtl number systems (such as galaxies and clusters)? Further, how does it depend on the Mach number of the flow?

4.5 What is being done to address the problems

4.5.1 Magnetic fields in gaseous medium of nearby galaxies

The ratio of radio and far-infrared (FIR) flux density is known to be well correlated among galaxies both globally and locally up to certain length scales. This correlation is explained by close coupling of gas and magnetic fields with the form $B \propto \rho^k$ [133, 159]. Equipartition magnetic fields derived from synchrotron emissivity and spectrum provide their fields strengths in galactic arms, interarms and in halos. Earlier works have been carried out on only a handful of nearby spirals. High resolution observations of ~ 10 more nearby galaxies have already been carried out with the GMRT metrewave band and observations of a complete sample (about 50 galaxies) of large galaxies within 11 Mpc have been planned with the upgraded GMRT (uGMRT) as part of PhD thesis of a student.

It would also be useful to compare the fields in nearby spirals with the nearby ellipticals. Due to lack of large scale rotation, theoretical models [142] predict almost no large scale field in elliptical galaxies, and random fields could also be lower than in spirals due to low star formation activity. A few of the nearby early type galaxies are being observed with GMRT to detect non-thermal radio emission and magnetic fields (S. Roy & K. Subramanian).

4.5.2 Probing magnetic fields at high redshifts

Strong, singly ionized magnesium (Mg II) absorption line in the quasar spectra has been used as a proxy for inferring the existence of an intervening galaxy along the line of sight. By using the correlation between the number of Mg II absorbers and the magnitude of the rotation measure (RM), work by a number of authors [e.g., 113, 112, 135, 124, 140] has revealed the existence of μG strength magnetic fields in young galaxies at redshifts $z \sim 1$, that are of comparable strengths to those that are observed in galaxies of today. The discovery of these strong magnetic fields has sparked critical questions regarding

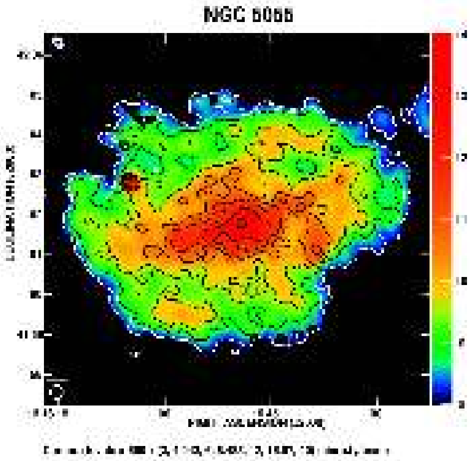

Figure 4.1: Colour coded image of the equipartition magnetic fields of the galaxy NGC 5055 (resolution 20″). Contours show continuum radio emission at 330 MHz. Adapted from Basu & Roy [109], Basu et al. [110].

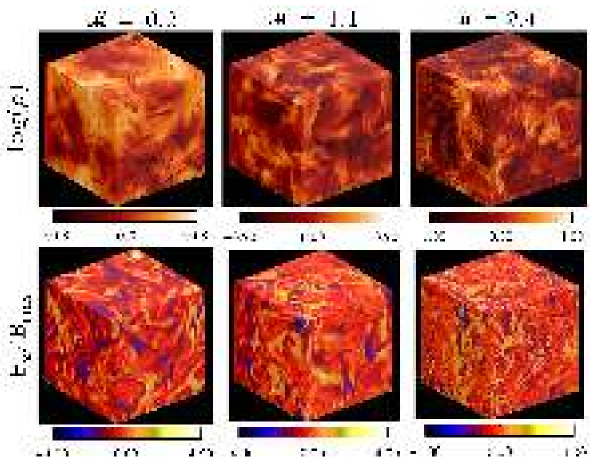

Figure 4.2: Shown column-wise : 3D volume renderings of the density (upper row) and B_z/B_{rms} (lower row) in the saturated phase for Mach numbers $\mathcal{M} = 0.3$(left), 1.1 (middle) and 2.4 (right), respectively. Adapted from Sur et al. [157].

their generation mechanism and their degree of coherence. It is plausible that such fields can arise from fluctuation dynamo action due to their short amplification time scale ($\sim 10^7$ yr).

In a recent study, Sur et al. [157] performed a suite of fluctuation dynamo simulations including transonic and supersonic flows up to Mach numbers of 2.4 (Fig. 2). The aim was to probe if the generated fields were coherent enough and the extent to which the Faraday RM compared with observational estimates from MgII absorption systems. They obtained rms values of RM at dynamo saturation of the $\sim$45−55% of the value expected in a model where fields are assumed to be coherent on the forcing scale of turbulence. This lead to a random RM of $16 - 48$ rad m^{-2}, consistent with observations of Farnes et al. [124].

4.5.3 Probing magnetic fields in galaxy clusters and cosmic filaments

Galaxy clusters are found to be magnetised and these fields are important in understanding the physical processes in the intra cluster medium which are also magnetised. Several large scale (few Mpc) features from the clusters have already been detected [108] with surface brightness of the order of few tens of μJy/arc-sec^2 at 1.4 GHz. Central region of clusters often host diffuse radio halos of non thermal synchrotron emission [129]. It is believed that most of the baryons in the universe are actually residing in cosmic filaments and groups.

One of us [146, 145] is involved in modelling the magnetic field and non-thermal emissions from these clusters and filaments using cosmological simulations and has computed its detectability with the upcoming SKA telescopes.

4.5.4 Current status of theoretical work

A potential problem associated with mean-field dynamos is the rapid growth of small-scale magnetic helicity as a consequence of magnetic helicity conservation. This leads to catastrophic quenching of the large-scale dynamo even before the field reaches a steady state. While *helicity fluxes* [154, 151] has been proposed as a possible solution, it has brought to the fore another fundamental question : how do mean-field dynamos operate in the presence of rapidly growing small-scale magnetic fluctuations? Current efforts to resolve this issue found that instead of a separate mean-field dynamo independent of fluctuation dynamo, there is only a *unified dynamo* where initially, all scales grow together at one rate [115] with the largest scales continuing to grow (aided by small-scale helicity loss) as the small-scale field saturate.

On the other hand, while most of the numerical work on fluctuation dynamos was concentrated on field amplification in incompressible turbulence, we now have a significant body of work where these dynamos have been also explored using simpler setups for transonic and supersonic flows likely to occur in the ISM of galaxies. These studies have revealed key insights on the efficiency, amplification rates and saturation levels as well as on the three-dimensional nature of the field configuration, depending on the compressibility of the flow [125, 158]. However, despite these remarkable advancements, the question of the degree of coherence of the field in the saturated state has remained a bone of contention. Resolving this issue is crucial in the sense that if most power is concentrated in small scales, it would lead of insufficient degree of coherence and negligible RM values, inconsistent with observations. High resolution simulations at $P_{\rm m} \gg 1$ with $\mathrm{Re}, \mathrm{Re}_M \gg 1$ are required to settle this issue.

With the advent of powerful supercomputers and sophisticated numerical algorithms it has now become possible to perform dynamo simulations in more complex settings that are closer to the realistic ISM and ICM. Employing solar neighbourhood values of the supernovae rate and gas surface densities typical of the Milky Way, simulations of magnetised ISM with and without shear have probed important issues such as : the effect of the field on the vertical structure, role of magnetic field in regulating disk-halo matter circulation, volume filling factors of the different ISM phases, integral scales of the mean and the random component of the field etc. [122, 130, 134, 127]. Magnetic fields in the ICM are generated by fluctuation dynamos. These fields can induce random Faraday RM from radio emission of background sources seen through the intermittent field generated by the dynamo. Indeed, simple driven turbulence in a box simulations show that these intermittent fields produce a sufficient degree of Faraday rotation, consistent with existing observational estimates [114, 157].

4.6 What can be done with the existing telescopes

The present sensitivity of JVLA with its one order of magnitude increase in bandwidth is several times better than the erstwhile VLA. This allows for wideband observations for rotation of polarisation angle, which in turn allows one to do Faraday tomography (Brentjens & de Bruyn 2005). RM synthesis can be employed to recover the RMs of individual Faraday screens when several of them are located along the same line-of-sight.

JVLA sensitivity at 4.5-6.5 GHz band does yield a few background polarised sources across any area of the sky of size $\sim 10'$ with a few hours of observation using the RM grid (Beck & Gaensler 2004). We consider various science cases which can be addressed with better sensitivity.

4.6.1 Magnetic fields in our Galaxy

Milky Way is an ideal test bed for studying magnetic fields in great details. Study of the fields in discrete objects like molecular clouds, supernova remnants, HII regions, planetary nebulae and in small scales (<10 pc) are best explored in detail in the Galaxy. The dynamo mode most easily excited is axisymmetric and has even parity with respect to the mid plane. The toroidal and radial component forms an axisymmetric spiral pattern.

As discussed above, JVLA sensitivity do allow to determine the RM/Faraday-depth (FD) towards several background sources in each $10'$ region seen through the Galaxy. This will allow better disentangling of local effects from the systematic ones in our Galaxy, and quite detailed mapping of magnetic fields in the Galaxy. However, the time required is too large for generic surveys to probe magnetic fields of our Galaxy with RM grid. We discuss further advancement that is possible in this area in a later section.

Magnetic fields near the central region and in discrete objects

Galactic centre (GC): Studying magnetic fields in the central region (∼100 pcs) of our Galaxy with a high resolution is important to understand the same in other nearby spiral galaxies. Large uncertainties exist in determining the field strength in this region. From synchrotron emission, the estimated minimum energy magnetic field is ∼10 μG. However, synchrotron spectral break indicates the strength is at least ∼50 μG [120]. Using RM grid measurements towards background sources, Roy et al. [148, 147] estimated a field strength of ∼20 μG. The large scale Fermi bubbles seen perpendicular to plane could form due to occasional formation of jets due to the central black hole, or from stellar activity in the central 1 degree region ($\sim$150 pc) region of the Galaxy [121, 119].

RM grid observations with JVLA will detect background polarised sources every about $5-10'$ along l and bi with observing time of few tens of minutes for every fields in 4-8 GHz band. This will enable detailed study of RMs through the GC ISM. This should provide much better constraints on the magnetic field models in the region. Observations in $\sim 4.5-6.5$ GHz will avoid significant depolarization due to any high RMs in the region.

Supernova remnants (SNRs): SNRs are the main drivers of turbulence and cosmic rays in the ISM. Magnetic fields in SNRs can be enhanced to mG strengths due to shock-induced compression. Measuring magnetic fields through RM grid for a large ($\sim$10) sample of large angular sized SNRs will shed light on any relationship of local Galactic magnetic fields [137] and/or the progenitor fields in the evolution of the SNR and its magnetic fields [131].

4.6.2 Probing magnetic fields at intermediate redshifts

Targeted deep observations are being made with JVLA towards nearby and intermediate redshift galaxies to unravel their magnetic field structures much better than what was possible a decade back. This has already shown microGauss strength coherent magnetic fields in a galaxy with redshift of 0.44 (Mao et al., 2017, NatAs, 1, 621).

4.6.3 Rotation measure synthesis of ISM of nearby galaxies

At frequencies below about 1.4 GHz, internal depolarization is present everywhere in galaxies and causes a frequency-dependent modulation of the degree of polarisation. Using the methodology of RM synthesis as described earlier, it provides a great deal of information about the physical conditions in ISM of nearby galaxies. Through detailed modelling of depolarisation, 3-dimensional structure of the Faraday screen and magnetic fields in the ISM of galaxies can be unveiled in great detail (Heald et al. 2015). This is complementary to higher-frequency RM grid observations discussed earlier, which suffers little from depolarization. The upgraded Giant Metrewave Radio Telescope (uGMRT) have observing band from $550-850$ and $1000-1400$ MHz. These bands of GMRT can be used to study magnetic fields and ISM in nearby galaxies through RM synthesis before SKA1 survey band 2 is operational. However, this would require good polarisation calibration of the system.

4.7 Why do we need SKA for addressing the problems

As mention earlier, SKA and its precursors will have much higher sensitivity, which will result in finding polarised emission towards sources with much lower flux densities than is possible now. These telescopes will have simultaneous wide band coverage with smaller synthesised beam ($\sim 1''$ at 1.4 GHz with SKA-I). This will result in much lower beam averaging of any polarised emission. We discuss some of the science cases which will be pursued because of the above advantages.

4.7.1 Magnetic field in our Galaxy

As discussed in Haverkorn et al. [132], comparing the predictions of dynamo theory with the current observational data of the Galactic magnetic fields is still difficult. There is still claim that the large scale field is axisymmetric [160] or bisymmetric [143]. The difficulty stems from *local* structures like the local magnetised bubble [156], low density of polarised sources [152] and uncertain distance estimates of pulsars used for RM and dispersion measure estimates.

SKA-I resolution and sensitivity will yield several tens of background polarised sources across any area of the sky of size $\sim 10'$ with an hour of observation using the RM grid. This will allow to determine the RM/FD towards these sources. This will allow disentangling of local effects from the systematic ones in our Galaxy, and detailed mapping of magnetic fields.

Pulsar RM surveys with dependable distance estimate will also probe magnetic fields along many different directions. It is estimated that SKA1-Low and SKA1-MID will discover $\sim$20,000 pulsars in the Galaxy [138]. This will help to model the magnetic fields in the Galaxy.

Magnetic fields in discrete objects of the Galaxy

Molecular clouds: Magnetic fields could play an important role in star formation [139]. However, due to lack of accurate measurements, its role has not been properly understood. Intensity of in-situ synchrotron radiation from these clouds could be used to estimate strength of magnetic fields in such clouds [144, 123]. SKA-1 Mid resolution and sensitivity will be good enough to detect such emissions (∼mJy) from cloud cores (ang.-size $\sim 1''$ at ∼kpc distance).

4.7.2 Probing magnetic fields at high redshifts

As discussed in Sect. 5.2, the occurrence of strong magnetic fields in young galaxies having strengths similar to the ones observed in nearby galaxies needs to be understood. Observationally, an accurate estimate of the field orientation and the degree of order will require measurement of the Faraday RM through a large number of polarised extragalactic sources. To achieve this, one must aim for the highest angular resolution with SKA-I having sufficiently large signal-to-noise ratios and maximum polarised intensity such that Faraday depolarization effects are negligible. At the heart of SKA's study of cosmic magnetism will be an All Sky Rotation Measure survey, which will yield RMs for $\sim 2 \times 10^7$ compact polarised extragalactic sources in a year of observing time [126]; an increase by three orders of magnitude over what could be observed by JVLA. The data sets are expected to provide an all-sky RM grid at a spacing of $\sim 90''$ between the extragalactic sources [126].

As a caveat, we note here that fields at high redshift, even if unorganised, can be detected via their resulting synchrotron emission. However, while the energy losses of cosmic ray electrons due to inverse Compton scattering off CMB photons are negligible in the local Universe, the rapid increase of the CMB energy density by a factor $\sim (1+z)^4$ indicates that detecting synchrotron emission beyond a critical redshift will not be possible. SKA-I is expected to detect ∼5000 galaxies per square degree above 10 σ, which implies that it can probe magnetic fields in ∼50,000 galaxies out to red-shift $z > 4$ for a 10 square degree survey (Taylor et al. 2015).

Probing magnetic fields galaxy clusters

The SKA will enable the detection of many polarised sources through an individual cluster and thus map the magnetic fields in it. One would also detect many more radio halos. In particular, the enhanced sensitivity and improved angular resolution of SKA will allow one to detect polarization, which has been seen in very few radio halos at present.

Magnetic fields in AGN parsec scale jets

Blazars are core-dominated Active Galactic Nuclei (AGNs) and are characterised by a luminous core and rapid variability over entire electro magnetic spectra. Core-jet morphology is a common characteristic of most of the AGNs in Very Long Baseline Interferometry (VLBI) images, where core is the optically thick base of the jet [116] with its absolute position being the surface in the continuous flow where optical depth becomes close to unity. According to [136], absolute position of the VLBI core moves increasingly outwards along the relativistic jet with higher wavelength which can be attributed to the Synchrotron Self-Absorption process (SSA), calling this effect as frequency-dependent core shift. A new technique is used for extracting core shifts along with other physical parameters of jet using frequency dependent time lags for single dish observations [141, 107]. Radio continuum surveys with the SKA can provide AGN imaging and timing (flux density, polarization) data across a range of frequencies simultaneously, ideally suited for the application of the time delay method. This could yield the magnetic field in central pc of the core.

4.8 How do we plan to use SKA to address the problems

Many of the unsolved questions on magnetic fields can be probed with the sensitivity and resolution of SKA-I. As discussed above, one of the main approach to measure magnetic fields would be using RM grid by observing polarisation properties of the background sources Detecting polarised sources are better performed with resolutions of about $1''$ or better. SKA1-MID band 4 from 2.8−5 GHz is well suited. It provides detection of minimum RM/FD of a few tens of rad.m^{-2} and can detect FD up to about 500 rad.m^{-2} [111]. Typical sensitivity would be about 0.2 μJY/beam with integration time of 12 h. It is likely that before performing a whole sky polarisation survey involving observations over several thousand hours with bandwidths of several GHz having several thousands of spectral channels, certain parts of the sky will be observed with observing time of a few hundred hours to determine the effectiveness of the method and the scientific yield.

Already several scientists across the world are working on various aspects of planning such a survey. The survey is likely to be a team effort where a few of us are expected to be part of the team.

4.9 Anticipated results

1. Survey by SKA-I will yield a detailed map of magnetic fields in our and nearby galaxies, which will help to constrain the models of magnetic field amplification and maintenance in galaxies.

2. Deep observations of high redshift galaxies and clusters will yield a new frontier in our knowledge of origin of magnetic fields and its time evolution.

Synergy with other groups

(a) Magnetic field measurements using Zeeman splitting of HI would enable synergy with HI working group and (b) observations of background source for RM grid would enable synergy with Epoch of re-ionisation group as they would use these background sources as part of foreground estimation.

4.10 List of people currently active in India

(i) Prof. Arun Mangalam (IIA Bangalore), (ii) Dr. H. Chand (ARIES, Nainital), (iii) Prof. Kandaswamy Subramanian (IUCAA, Pune), (iv) Dr. P. Dutta (IIT BHU, Varanasi), (v) Dr. S. Paul (S P Pune University, Pune), (vi) Dr. Subhashis Roy (NCRA-TIFR, Pune), (vii) Dr. Sharanya Sur (IIA Bangalore), (viii) Prof. T. R. Seshadri (University of Delhi)

Chapter 5

Unveiling galaxy evolution through large HI 21-cm and OH 18-cm spectral line surveys with SKA

Neeraj Gupta and Nirupam Roy

References yet to be fixed

5.1 Executive Summary

To understand galaxy evolution through HI 21-cm line is one of the key drivers of SKA. 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 the Indian community have been presented here. It is reasonable to suggest that from the experience gained through various ongoing and upcoming efforts by the Indian community and/or by using the SKA pathfinder uGMRT, the community will be in an excellent position to take lead in these areas with SKA.

5.2 Scientific background

The atomic hydrogen (HI) is most abundant element in the Universe and it plays a fundamental role in the life cycle of galaxies. Hence, the HI 21 cm line is an important tool to study galaxy formation and evolution over cosmological timescale. The observations of HI 21-cm line in emission can be used to determine the distribution and kinematics of atomic gas in galaxies. HI 21-cm absorption lines detected in the spectra of background radio sources are more sensitive to cooler atomic gas component. These when combined with 21-cm emission line measurements, provide a direct measurement of spin temperatures (T_s) that can be used to constrain the gas kinetic temperature. However, observing 21-cm emission from galaxies at redshift of cosmological interest with existing instrument is a challenging task.

In the Milky Way, there have been many surveys for HI 21-cm emission and absorption line. Consequently, it is known that the atomic gas is present in two dominant phases: the cold (100K) and warm (8000K) neutral medium (i.e. CNM and WNM; e.g. Heiles & Troland 2003, ApJ, 586, 1067). In the local Universe, blind HI 21-cm emission line surveys using single dish telescopes have provided reliable measurements of the overall neutral gas content i.e. HI mass density ($?_{HI}$; see, for example, Zwaan et al. 2005, MNRAS, 315, L30) of the Universe. These surveys have been complemented with spatially resolved HI 21-cm emission line images obtained using radio interferometers to trace the large scale dynamics of galaxies, the distribution of dark matter and impact of environmental interactions (e.g. Haynes, Giovanelli & Roberts 1979; Bosma 1981; Fisher & Tully 1981; Rosenberg & Schneider 2002; Meyer et al. 2004; Walter et al. 2008; de Blok et al. 2008; Leroy et al. 2008, AJ, 136, 2782).

In short, over the decades, the radio observations of galaxies through HI 21-cm line in emission and absorption have emerged as a major tool to determine distribution, kinematics and physical conditions

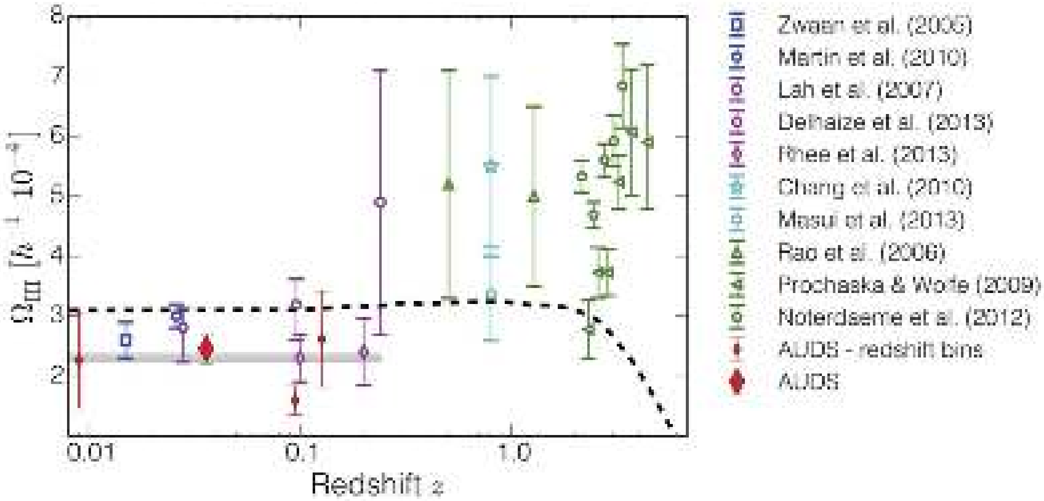

Figure 5.1: Evolution of the cosmic Ω_{HI} density with redshift (reproduced from Hoppmann et al. 2015, MNRAS, 452, 3726). The color corresponds to the type of measurement. Red, blue and magenta: HI emission (direct detection and stacking) surveys; Cyan: intensity mapping and Green: Lyα absorption spectra. Note the lack of constraints at $0.2 < z < 2$. Beyond the local Universe, the Ω_{HI} is either poorly determined or is based on optical observations damped Lyα absorbers (DLAs) that may be systematically biased against regions with high metallicity and dust.

in neutral interstellar medium (ISM) of galaxies. However, due to the limited sensitivity of present day radio telescopes most of these studies are limited to the local Universe (z<0.2). The current highest redshift HI 21-cm emission detection is from a galaxy at z0.36 using very long integration (178 hrs; Fernandez et al. 2016, ApJ, 824, L1) with VLA.

Unlike 21-cm emission, detectability of 21-cm absorption doesn't depend on the distance of absorbing galaxy. However, due to the limitations imposed by the narrow receiver bandwidths and the hostile radio-frequency (RFI) environment, blind searches of 21-cm absorption haven't been possible and only 50 intervening HI 21-cm absorbers at 0<z<3.5 are known. For a different class of absorbers - associated HI absorbers - where the gas is associated with a active galactic nuclei (AGN), more than 100 absorbers are known but most of these are at z<0.5.

5.3 Contribution by Indian community

Over the years, the Indian astronomy community has utilized (1) hybrid array configuration of GMRT which allows simultaneous imaging of compact and large scale diffuse structures, and (2) low-frequency coverage which allows observations of HI from galaxies at higher redshifts. A few of the significant Indian contributions to HI emission and absorption studies of galaxies using GMRT are: (i) systematic HI emission line observations of dwarf and low-metallicity galaxies in the nearby Universe (e.g. Begum et al. 2008, MNRAS, 386, 1667), (ii) deep HI emission line observations of star forming galaxies at z>0.2 (e.g. Lah et al. 2007, MNRAS, 376, 1357), (iii) systematic HI and OH absorption line surveys to probe atomic and molecular gas content of active galactic nuclei (e.g. Gupta et al. 2006, MNRAS, 373, 972) and normal galaxies (e.g. Gupta et al. 2012, A&A, 544, 21; Kanekar et al. 2014, MNRAS, 438, 2131; Dutta et al. 2017, MNRAS, 465, 588) at 0<z<3.5, and (iv) most sensitive constraints (1 ppm) on fractional variations of fundamental constants of physics (e.g. Kanekar et al. 2005, PhRvL, 95z1301; Rahmani et al. 2012, MNRAS, 425, 556).

5.4 Unsolved/outstanding scientific topics

Despite major efforts from the radio astronomy community over last several decades, very little is known about the evolution of atomic gas in galaxies. Extending the scope of HI 21-cm line observations of

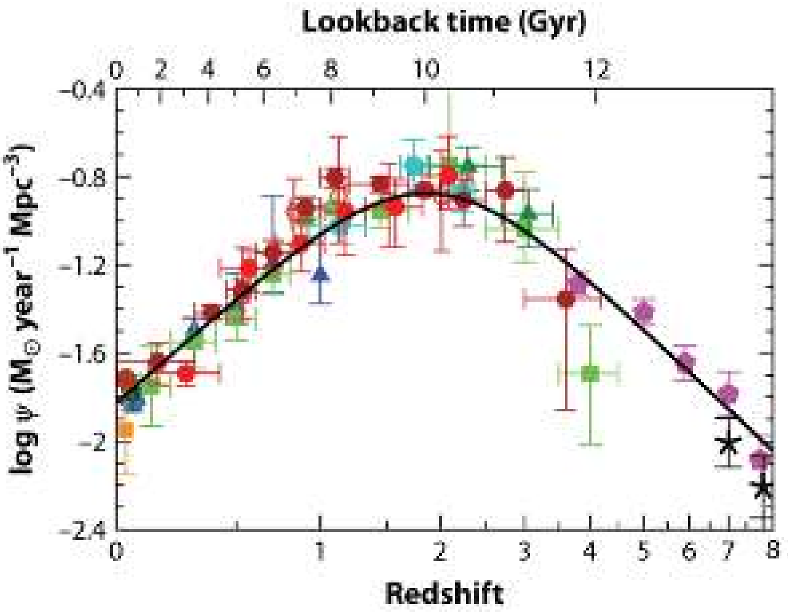

Figure 5.2: Star formation rate density as a function of redshift (Madau et al. 2014, ARA&A, 52,415).

galaxies is one of the key science drivers of SKA and all the upcoming SKA pathfinders. The study of cold atomic gas in galaxies via HI 21-cm absorption is already a key aspect in all the SKA precursor projects under way with APERTIF, ASKAP, MeerKAT and uGMRT, in which the Indian astronomy community is deeply involved and already playing a lead role. Similarly, large blind surveys of HI 21-cm emission with the SKA covering larger redshift range will be useful in studying evolution of HI mass function as well as cosmic baryonic fraction. The key science themes that will be advanced by HI 21-cm surveys with SKA are outlined below.

1. **Evolution of cold gas in galaxies and relationship with star formation rate (SFR) density:** In recent years, tremendous efforts have been dedicated to establish the evolution of the global comoving SFR density. The observations show that there is a peak in the comoving SFR density between $1<z<3$ followed by an order of magnitude decrease towards z0 over the last 10 Gyrs i.e. 70% of the age of the Universe (Bouwens et al. 2014, ApJ, 795, 126; see Fig. 2). But a clear picture of underlying processes that drive such a strong evolution is yet to emerge.

   Since stars form in molecular clouds, the observations of molecular gas (H_2), which is the basic fuel for star formation, and the atomic gas (HI), which is the dominant gas component of galactic discs, can be used to understand the evolution of SFR density. The upcoming large absorption line surveys with SKA pathfinders will use HI 21-cm and OH 18-cm absorption lines to trace the evolution of cold atomic and molecular gas phases of galaxies. Among these surveys, the MeerKAT Absorption Line Survey (MALS; *PIs: N. Gupta and R. Srianand, IUCAA, India; Gupta et al. 2017, arXiv: 1708.07371*) to be carried out at the South African SKA precursor (MeerKAT) during 2018 - 2023 is particularly distinguishable. It is the only survey that will uniformly cover $0<z<1.5$, the redshift range of interest as far as the evolution of SFR is concerned (cf. columns 2-3 of Table 1). In particular, both in the L- and UHF-bands it covers more than 50% of the redshift ranges inaccessible to any of the other planned surveys. Through MALS, the detection of 200 intervening absorbers is expected.

   The SKA science book outlines a number of fiducial HI surveys covering 1000 - 10,000 deg^2 that the international astronomy community would like to take up with SKA-mid and -low. These would lead to detection of several thousand intervening HI 21-cm absorbers at $0<z<8$. This would provide reliable estimates of cold atomic and molecular gas cross-section of galaxies and will be key observables to understand the process of warm gas into cold atomic and molecular gas, and eventually stars.

   The absorbers from these surveys will be followed-up using very long-baseline interferometry at radio wavelengths and sensitive optical telescopes such as SALT and TMT, in both of which India is a partner country, to map the pc-scale structure in the ISM (Srianand et al. 2010, MNRAS, 428, 2198) and constrain physical parameters such as metallicity, density, temperature and ambient radiation field in the ISM of high-z galaxies. These parameters in addition to the measurements of cold gas cross-section of galaxies from the absorption line surveys will be valuable inputs to test and refine physical models of the ISM so far based primarily on the galactic ISM (Wolfire et al. 2003, ApJ, 587, 278) and understand the processes driving the evolution of SFR density.

2. **Fuelling of AGN, AGN feedback and dust-obscured AGNs:** AGN activity is known peak during the same epoch as SFR density. Both theoretical and observational considerations suggest a close relationship between galaxy evolution and AGN activity. Further, the existence of red i.e. dust-obscured AGNs is predicted in both the orientation-based AGN unification models and the evolutionary scenarios but the exact fraction of such AGNs is still uncertain with estimates ranging over 10 - 50%. Through a dust-unbiased search, the SKA pathfinder surveys (Table 1) will detect more than 1000 associated HI and, an unknown number of, OH absorbers. Through these the surveys will determine the (1) distribution and kinematics of atomic and molecular phases associated with circumnuclear gas and the ISM of AGN hosts, and (2) the fraction of dust-obscured AGNs missed out in optical/ultraviolet surveys.

   But the SKA pathfinder surveys will mostly be limited to most powerful AGNs (10^{24}W Hz^{-1}) and detect only the strongest absorption components. The more sensitive surveys with SKA will, for the first time, enable detection of cold gas in low-power AGNs. There will also be substantial number (at least several 100) detections of broad low optical depth blue-shifted (>1000 km/s) absorbers representing gas outflows (Morganti et al. 2005, A&A, 444, L9). The evolution of the detection rate of these outflows and the mass-outflow rate is a key observable to compare with the predictions from models of galaxy evolution.

3. **Constraining space- and time-variation of fundamental constants of physics:** The absorption lines seen in the spectra of distant QSOs can be used to place constraints on the space and time variations of different dimensionless fundamental constants of physics (Uzan 2003, RvMP, 75, 403). For the past decade or so based on systematic efforts using high resolution echelle spectrographs at VLT and KECK, we have constrained the variation of ?=(e^2/hc) and ?=(m_e/m_p) at the level of 1 ppm at high-z. The next major step would be to improve these constraints by another factor of 10 i.e. 1 part in 10^7 which will be comparable to local measurements based on atomic clocks. The major systematics that prevents any further improvement is due to the stability of wavelength scales in present day optical spectrographs (Rahmani et al. 2013, MNRAS, 435, 861; Whitmore & Murphy 2015, MNRAS, 447, 446). Further progress is possible through radio absorption lines because the frequency scales at radio telescopes are known to be well defined (e.g. Bagdonaite et al. 2013, Sci, 339, 46) and compared to optical/ultraviolet lines the radio lines are more sensitive to the variation of fundamental constants. But a large sample of radio absorbers is required to achieve this so that any systematics introduced due to ionisation, radiation and excitation inhomogeneities in the gas that gets reflected as the variation of constants is randomised. Blind surveys with SKA will provide a large sample at $0<z<8$ to achieve this for the first time. Through main- and satellite- OH absorption lines from the survey, or the joint analysis of 21-cm and OH absorption with various metal, atomic and molecular absorption lines detected through follow-ups with ALMA, NOEMA, VLA, VLT and SALT the survey will lead to tightest constraints on the variations of fundamental constants of physics.

4. **Evolution of magnetic fields in galaxies:** Magnetic fields are known to be present over a wide range of physical scales in astrophysics. They are an important component in the energy balance of the ISM. Besides being important in determining the conditions for the onset of star formation in protostellar clouds they are also relevant for (i) the formation and stabilization of gas disc and spiral arms, (ii) the heating of gas, especially, in the outer discs and halos, and (iii) the launching of galactic outflows and determining how the matter and energy are distributed throughout the galaxy. Overall they are tightly coupled to various stellar feedback processes and play an important role in a wide range of physical processes that drive galaxy evolution (e.g. Bhatt & Subramaniam, 2013, MNRAS, 429, 2469).

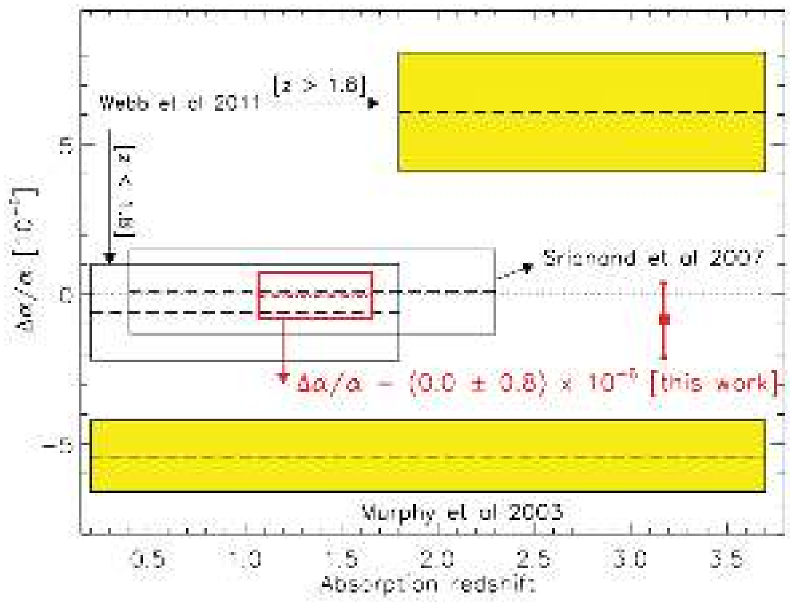

Figure 5.3: Comparison of constraints of fine-structure constant based on various radio and optical studies (Rahmani et al. 2010). The surveys with SKA will improve these by an order of magnitude and will also address systematics in measurements.

Although magnetic fields can be observed throughout the electromagnetic spectrum, the most successful and direct approach to map the magnetic fields in galaxies is via imaging of the polarized synchrotron emission at a few GHz. However, such observations have been limited to small samples of galaxies in the Local Volume. It has been difficult to undertake these studies for a large number of and/or objects beyond the local Universe due to limits in sensitivity, spatial resolution and broadband coverage offered by current telescopes.

5.5 On-going work

The extreme sensitivity and RFI-free environment of SKA will enable large blind absorption line surveys of HI 21-cm and OH 18-cm lines at $0<z<8$. A summary of blind absorption line surveys already underway with SKA pathfinders is provided in Table 1. From these several hundred intervening HI 21-cm absorbers will be detected. A similar number of another class of absorbers - *associated* absorption - where the gas is associated with the host of an Active Galactic Nuclei (AGN) will also be detected. At present only about 100 associated HI 21-cm absorbers are known and the bulk of these are at $z<0.5$ (Gupta et al. 2006, MNRAS, 373, 972; Aditya et al. 2018, MNRAS, 473, 59). Therefore, these surveys represent a major step towards mapping the evolution of cold gas in galaxies using radio absorption lines.

In a similar way, HI 21-cm emission surveys are also either being carried out or planned to be with the pathfinders (e.g. WALLABY large area survey for $z<0.25$ with the ASKAP, LADUMA with the MeerKAT for smaller region of Extended CDFS but till larger redshift of $z<1.4$ etc.) as steps towards the HI emission line survey with the SKA low and mid.

5.6 Possibilities using current telescopes

The existing and upcoming telescopes like the upgraded GMRT will play a leading role in addressing some of these key questions, as well as allow us to carefully plan the future SKA observations in the most effective way. The uGMRT, along with other pathfinders, can be utilized to already carry out such studies to predict what to expect from the SKA low and mid observations. For example, some of the ongoing and upcoming moderately deep observations of well-studied deep-fields with the uGMRT 550

Table 1: Summary of various upcoming H I 21-cm absorption line surveys

Survey	Frequency coverage (MHz)	Redshift range (H I 21-cm)	Time per pointing (hrs)	Spectral rms per ∼5 km s^{-1} (mJy/b)†	Sky coverage (deg^2)	Total time (hrs)	No. of sight lines‡
Apertif SHARP	1130 - 1430	0 - 0.26	12	1.3	4000	6000	25000 (>30 mJy)
ASKAP FLASH	700 - 1000	0.5 - 1.02	2	3.8	25000	1600	65000 (>90 mJy)
ASKAP WALLABY	1130 - 1430	0 - 0.26	8	1.6	30000	8000	132000 (>40 mJy)
MALS L-band	900 - 1670	0 - 0.57	1	0.5	1000	691	12000 (>15 mJy)
MALS UHF-band	580 - 1015	0.4 - 1.44	2	0.6	700	746	12000 (>15 mJy)

† Estimated at the center of the band; ‡ See text for details.

- 900 MHz band as well as 1000 - 1450 MHz band (blind search with large bandwidth) will now give us the opportunity to detect individual gas rich galaxies (HI mass 10^11 solar mass) in a few hundred hours of integration time up to z 1. Using extensive spectroscopic catalogues for such fields, it is also possible to use spectral stacking for hundreds of normal as well as star forming galaxies to study the statistical properties and redshift evolution of galaxies with an order of magnitude lower HI mass. Note that such deep observation will also results in a variety of other scientifically worth output like properties of sub-mJy source population, radio continuum properties of star forming galaxies at high z etc. which will be of great interest to the community. In a similar venture, uGMRT is being used to probe the now accessible large redshift range for observing intervening and associated HI 21-cm absorption for substantially large samples.

5.7 Why SKA and how to use SKA for this?

However, even with the improved sensitivity and large instantaneous bandwidth of the pathfinders like the uGMRT, it remains challenging to carry out deep and blind HI emission or absorption survey to high redshift for a reasonably large volume. Extending the studies to larger redshift range and volume is crucial in reliably addressing the key questions mentioned above. 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 the galaxy evolution.

SKA through its unprecedented sensitivity, spatial resolution and broadband coverage will make breakthrough observations in this field. Rotation measure and Zeeman splitting observations of large number of 21-cm absorbers detected from >1000 hrs blind absorption surveys will, for the first time, provide a direct measurement of magnetic fields in the discs of galaxies.

The SKA will enable HI absorption line studies to sub-mJy population of radio sources. With the SKA, modest (a few 100 hr) observations covering 1000 deg^2 will lead to detection of a few thousand associated and intervening HI absorbers (cf. next section). Such observations will most likely be carried out commensally with other radio continuum and polarization surveys.

In this context it is important to note that, thanks to large multi-wavelength surveys, quasars have already been detected out to z7.5. Excitingly, in recent years ALMA observations have shown that the host galaxies of quasars at z>6 are associated with large amounts of dust and molecular gas, and high inferred star formation rates (e.g. Decarli et al. 2018, ApJ, 854, 97). The ALMA observations will be crucial to determine SFRs and, even, redshifts of these high-z galaxies and quasars which will be targets of observations with the SKA.

5.8 Desired observation details and Anticipated results

The scientific yield of an absorption line survey is based on the optimization of following two parameters that solely drive the number of detections and the science output from the survey:

1. Optical depth sensitivity (??dv): The target 5? integrated optical depth sensitivity for intervening HI 21-cm absorption surveys with SKA will be ??dv=0.045 km s^{-1}. This corresponds to a sensitivity to detect CNM in N(HI)10^{19} cm^{-2} gas via HI 21-cm absorption. For associated absorbers the target peak optical depth sensitivity over 30 km/s will be 0.01.

2. Redshift coverage and Survey redshift path (?z): It is obvious that to cover the entire redshift range (0<z<8) both SKA-mid and -low will be needed. The total redshift path with target ??dv for intervening absorbers should be 10^5. For a blind absorption line survey with SKA over 1000 deg^2, the target optical depth sensitivity for associated absorbers will also be achieved.

We note that greater sensitivities or survey areas may be achievable for the absorption line science through surveys optimized for commensal HI emission and radio continuum science, or cosmology.

5.9 Number of person active in India

Currently, the HI SWG consists of about 20 researchers. With the advent of uGMRT this number is expected to increase in coming years.

Chapter 6

Neutron Star Physics in the SKA Era : Detailed Project Report

Sushan Konar[1], Manjari Bagchi, Debades Bandyopadhyay, Sarmistha Banik, Dipankar Bhattacharya, Sudip Bhattacharyya, Avinash A. Deshpande, R. T. Gangadhara, A. Gopakumar, Yashwant Gupta, B. C. Joshi, Biswajit Paul, Alak K. Ray

6.1 Executive Summary

Neutron star (NS) science with the SKA will happen mainly through all-sky surveys performed with high spatial and timing resolution. As the interests of the Indian community correspond closely to the SKA science goals, we envisage that formulation and execution of relevant observational projects (particularly, those defined using the ***upgraded GMRT*** and ***Astrosat***), supported by appropriate theoretical investigations is of great importance. Therefore, it is imperative that we set up the infrastructures required to complete these projects (in close collaboration with the international community) and start building a larger user community able to take advantage of the data products expected from the SKA.

6.2 Background

The history of neutron star astrophysics is strewn with rather prescient theoretical work since long before the actual observation. The serendipitous discovery of the first radio pulsar [206], and its subsequent identification with an NS, one of the most exotic objects in the Universe, is a watershed moment for theoretical astrophysics when the prediction [165] made three decades previously (only two years after the discovery of neutrons) was finally confirmed through observation. Landau 1938 strengthened the argument for their existence by showing that beyond a density of 10^{11} g cm^{-3}, electrons would combine with protons to form neutrons (again predating the discovery of neutrino, one of the byproducts, by almost two decades!). The physical conditions inside an NS are quite extreme - densities going up to and beyond the nuclear ($\sim 10^{15}$ g cm^{-3}) and magnetic fields ranging from 10^8 G to 10^{15} G. While Oppenheimer & Volkoff 1939 performed the first calculations for the interior structure; Hoyle, Narlikar & Wheeler 1964 argued that a magnetic field of 10^{10} G might exist in an NS at the centre of the Crab nebula. Just before the discovery, Pacini 1967 proposed that the rapid rotation of a highly magnetised NS might be the source of energy in the Crab nebula. Condensed stars were also predicted to be observable sources of X-rays in accreting binaries [205, 260] which received confirmation through the discovery of Her X-1 & Cen X-1 [191] by the X-ray satellite UHURU and their identification with accreting NSs. In recent years, it has also been established that NSs can have emission at energies as high as 100-GeV, where they are currently being detected by the two active gamma-ray observatories AGILE and Fermi.

Interestingly, at the time of their first prediction, NSs seemed to be completely beyond the possibility of actual observation. However, today the spectral range available for studying NSs extend from radio

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(down to 10 MHZ) to high energy gamma rays (above 100 GeV) covering over 20 decades of the electromagnetic spectrum, a range far wider than available for any other astronomical object. Yet, the NSs are still primarily observed as radio pulsars (of the ∼3000 known objects, more than 2500 are radio pulsars) implying that the study of the NSs is expected to receive an unprecedented boost in the SKA era through a many-fold increase in the number of observed NSs [251, 252].

6.3 Current Problems

At this point of time the main topics of NS research, which are also mostly concurrent with the SKA science goals, are [219] –

1. ***Population Studies*** – search & survey of radio pulsars, population synthesis and statistical studies of characteristic observational properties;
2. ***Evolutionary Pathways*** – evolution in HMXBs & LMXBs; importance of transitional pulsars (black-widows & red-backs); evolution of magnetic fields;
3. ***Magnetospheric Studies*** – emission physics; single pulse, micro & nano second studies; polarimetry;
4. ***Equations of State (EOS)*** – dense matter micro-physics; structure calculation; precise measurement of mass & moment of inertia;
5. ***Gravitational Physics*** – exploration of strong gravity regime using NS-NS, NS-BH binaries; gravitational wave detection using Indian Pulsar Timing Array (InPTA).

6.4 Indian Contributions

Right from the beginning NS research has been one of the focus areas of the Indian astrophysics community. In particular, the astrophysics group at Raman Research Institute, concentrating primarily on the theoretical aspects; and the scientists at National Centre for Radio Astrophysics, making use of the Ooty Radio Telescope (ORT) and later the Giant Meter-wave Radio Telescope (GMRT) for radio pulsar observations, have done some pioneering work. It needs to be noted that the Indian scientists have always possessed significant expertise in the three areas essential for NS research, namely - **i)** theory & simulation, **ii)** radio observation and **iii)** high-energy (X-ray) observation. Summary of the early work, as well as more recent updates, can be found in - Srinivasan 1995, Das & Chattopadhyay 2013, Chengalur & Gupta 2013, Chattopadhyay et al. 2015, Bhattacharya, Dwarakanath & Konar 2017. In the present document, we present a brief summary of the areas in which the Indian community have contributed significantly in recent years.

a) Population Synthesis - Population synthesis studies try to understand the cumulative properties of NSs in different ‘classes’ and the physics behind their observed properties. Two basic methods are generally adopted for such studies - the ‘snapshot’ method and the ‘full dynamical’ method; and sometimes an intermediate one [227, 204, 167, 193]. The ‘snapshot’ method the properties of a specific ‘class’ of objects are studied [208, 218, 240]. Consequently, it suffers from observational limitations and is not effective in uncovering all the characteristics of a given class. On the other hand, in the ‘dynamical’ method [173, 184, 257, 248] a set of initial parameters are chosen and the evolution of these parameters are obtained using numerical simulations. Finally, the choice of the initial parameters, the evolutionary models etc. are justified (or otherwise) by comparing the ‘observable’ properties of the synthetic set of objects with the actual observed results. This, therefore, has the potential to uncover hitherto unknown properties of the objects under investigation.

b) Evolutionary Pathways - In recent times, some ∼3000 odd NSs, showing disparate observational characteristics, have been sorted into three primary classes according to their mode of energy generation [215, 219] - **(a)** the rotation powered pulsars (RPP); **(b)** the accretion powered pulsars (APP); and **(c)** the class of internal energy powered NSs (IENS). One of the primary challenges of NS research has been to find a unifying theme to explain these different classes. The magnetic field, ranging from 10^8 G in millisecond radio pulsars (MSRP) to 10^{15} G in magnetars, has been central to this theme. It plays an important role in determining the evolution of the spin, the radiative properties and the interaction of a NS with its surrounding medium. Consequently, it is the evolution of the magnetic field which link these classes. Some of the evolutionary pathways have now become well established and a global unification scheme appears to be emerging [220]. In particular, the initial theory of MSRP generation in LMXBs [162, 244] and extensive follow-up work based on the evolution of the magnetic field is now widely accepted. However, a direct connection between MSRPs and LMXBs has been lacking since radio pulsations are not observed from LMXBs. Recently, three sources (PSR J1023+0038, PSR J1227-4853, PSR J1824-2452I) have shown transitions between the radio pulsar phase and the LMXB phase [163, 249, 239], confirming the transitional pathway. All the three transitional pulsars mentioned above are red-backs. The black-widow and the red-back pulsars are binary MSRPs, so named because they are in the process of destroying their companions through strong pulsar winds. Detection of OH-line absorption through radio line spectroscopy in intra-binary spaces around some MSRPs has recently been suggested [247] as a way of investigation into the physics of these systems. OH is usually formed by dissociation of the H_2O molecule, and it may give us a better understanding of past evolutionary history of such systems as well as the composition of the companions.

c) Magnetospheric Studies -

Pulsar Emission Physics : It became clear, early on, that the pulsed nature of the radio emission is due to a misalignment of the rotation and the magnetic axes [243]. The structure of the emission beam of a pulsar is currently described by a number of different models [229, 245, 190, 236]. Yet, a complete understanding of the physical mechanism responsible for pulsar emission is far from complete. The first tomographic studies of pulsar emission regions have been recently been conducted which promises to throw light on this issue [234]. Similarly, quite a few ideas have been developed to explain the polarisation characteristics of a pulsar profile [224, 223, 225].

Single Pulse Phenomena : Recent studies suggest that the magnetospheric changes responsible for nulling occur at a global scale [187]. The underlying periodicity and clustering of nulls and bursts in strong pulsars indicate the presence of a stochastic Poisson point process [186, 188]. Sub-pulse drifting or sub-pulse modulation involves modulations in single pulses which is indicative of physical processes having a range of timescales – milliseconds to hundreds of seconds. Though the phenomenological 'carousel model' has gained strong observational support [181, 182, 164, 211], inconsistencies have also been reported [183, 233].

Motion of emission point : It has been seen that relativistic effects change the location of the emission points [190, 195, 189] and are more pronounced in the millisecond pulsars.

Continuous/unpulsed/off-pulse Emission : Presence of a continuous emission component, i.e., emission in the off-pulse regime or far from the main pulse in the profile, has been long looked for. Recently, a new method has been proposed to detect off-pulse (unpulsed and/or continuous) emission from pulsars, using the intensity modulations associated with interstellar scintillation [246].

Faint Emissions : Faint radio emission from some of the gamma-ray pulsars, earlier considered to be *radio-quiet*, have been detected in recent times [242, 161, 232, 231, 235]. Unusual radio emission from these gamma-ray pulsars are likely to be detected in the form of "giant-pulses" [230].

d) Equation of State - Observed masses and radii of NSs are direct probes of the composition and the equation of state (EoS) of matter (review by [169]). In recent time, masses have been estimated to very high degree of accuracy by measuring post-Keplerian parameters. The composition of dense matter extracted from NS observations is also important for the construction of EoS tables for "core collapse - supernova explosion" (CC-SNe) simulations, NS mergers and understanding the appearance of strange matter in the early post bounce phase of a CC-SNe [170].

e) Gravitational Physics - NS-BH systems are of great importance for gravity studies. Because, the orbital dynamics of NS binaries are described in terms of five Keplerian and eight post-Keplerian parameters [177, 221, 228], and these have much greater values for NS-BH binaries [166, 168]. These are also useful for going beyond certain approximations while constructing gravitational wave inspiral templates [192, 194]. On the other hand, NS-WD binaries are excellent for probing possible variations of the gravitational constant G or to test strong equivalence principle [168].

6.5 Current Status & Future Plans

Even as we wait for the SKA to be built, it is important to develop scientific projects with the precursor and the pathfinder instruments, in order to prepare for the SKA. As is evident from the discussion

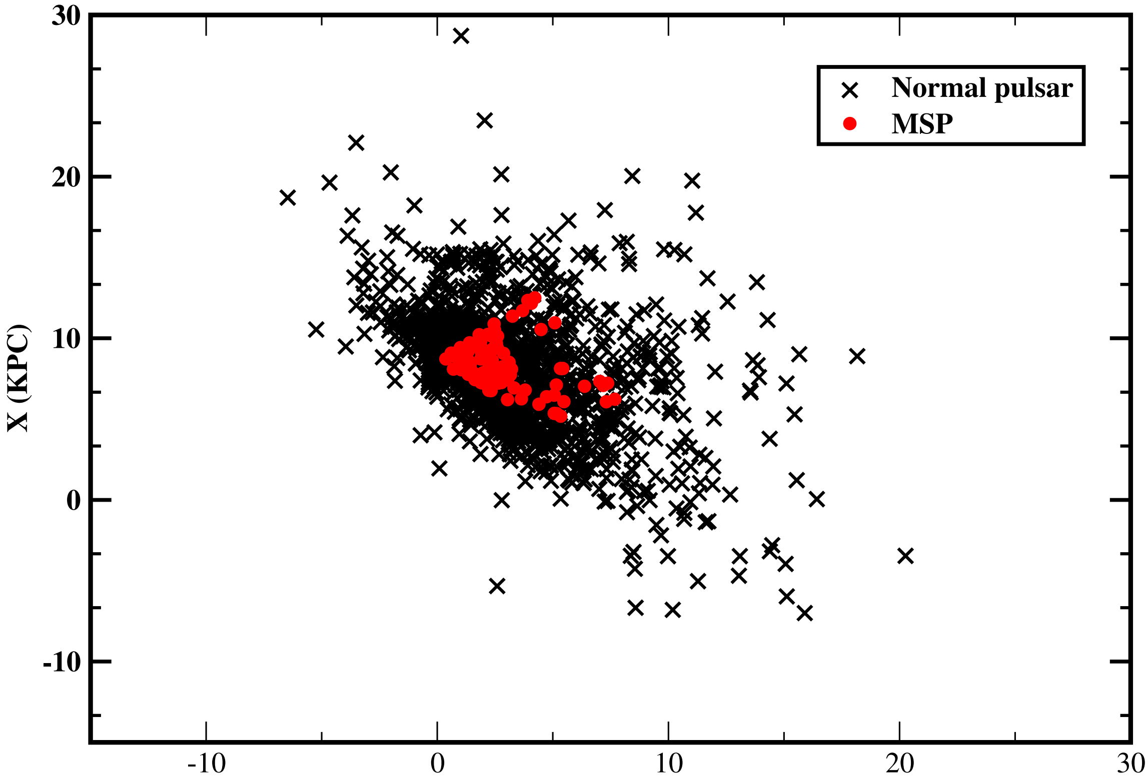

Figure 6.1: Distribution of expected RPP (normal + millisecond) discoveries projected onto the Galactic plane.

above, the Indian community is already pursuing many of the theoretical questions that are going to be of great importance. It is also involved in executing a number of observational projects using the upgraded GMRT, an *SKA pathfinder*. Moreover, the newly launched Indian X-ray satellite, Astrosat, is already improving our understanding of NSs in X-ray binaries and other X-ray emitting systems (review by [171]). Naturally, one of the focus of the Indian NS community is to undertake multi-messenger studies with uGMRT and Astrosat. Designing and execution of projects using the uGMRT, the Astrosat and making use of simultaneous observations with both of these instruments are already underway. Some of the main science projects being pursued by the Indian community and being planned for the future are summarised below.

Population Studies - Numerical population synthesis studies need to be combined with co-ordinated observational projects. The GMRT has been widely used for pulsar search [185, 203, 214] at low frequencies. The recent upgrade provides an opportunity to use 200 MHz instantaneous band-width between 300-500 MHz for a rapid survey of the sky, using the $\sim 80'$ primary beam. The frequency range for such a survey overlaps that of the SKA1-low and SKA-mid. Using an incoherent array of 30 antennas of the GMRT, with 4096 channels across the $300-500$ MHz bandwidth, a sampling time of about 80 μs and a dwell time of 300 s, the entire northern sky can be covered in about 1100 hours with the uGMRT. Even with a modest 200-250 hours of observing time per year, it can be completed well in advance of the commencement of science observations for the SKA1. The expected distribution of pulsars from this survey is indicated in Fig.[6.1].

A pilot project is already underway to prepare for such an 'all-sky' survey [198, 197, 196]. Preliminary results obtained from the pilot appear to justify the expectations above. Besides providing immediate science returns for the uGMRT, such a study has the potential to become a pathfinder survey for pulsar science with the SKA, commensurate with the *"pathfinder"* status of the uGMRT. Moreover, such a survey helps train young students making it a manpower development effort for the SKA.

InPTA - Pulsar Timing Array (PTA) uses an ensemble of pulsars (as accurate clocks) for detection of low-frequency gravitational waves (inaccessible by LIGO). Internationally, there exist three established

PTAs – a) Australian (PPTA), b) European (EPTA) and c) North American (NANOGrav) groups. The International Pulsar Timing Array (IPTA) is a collaborative umbrella for these three groups. The nascent Indian Pulsar Timing Array (InPTA) is on its away to become a formal member of the IPTA (some of the InPTA members are already active in various science working groups of IPTA). This effort started in 2016 with two sub-programmes: - (i) 9 pulsars were simultaneously timed with the GMRT (1400 MHz) and the ORT (327 MHz) [209, 210, 212, 213]; and (ii) 19 pulsars were timed in simultaneous dual (or triple) frequency mode using the wide-band systems of uGMRT band-5 (1000-1460 MHz), band-3 (250-500 MHz) and band-4 (550-850 MHz) in 200 MHz bandwidth coherent dedispersion mode [202, 201, 199, 200]. Both of these sub-projects are producing less than 10μs timing residuals and are also able to measure the time-dependent variations in the DM and scatter broadening. The data will be eventually released to IPTA.

6.6 Importance of the SKA

The SKA is expected to function as a rapid survey instrument. With the availability of large bandwidths (96 MHz and 300 MHz respectively for SKA1-low and mid) and integration time ($\sim$1800 second per position), the first phase of SKA is expected to find about 10000 new pulsars inclusive of $\sim$1500 millisecond ones. The full SKA is expected to triple these numbers, inclusive of a large number of transitional pulsars [216]. The most important impact of this huge increase in the number of observed NSs would be to provide a far clearer picture of the evolutionary paradigm. Many theoretical models are currently being developed which can be tested against the expected data [220].

Magnetospheric Studies - 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 the following studies. **a)** Studies of both null, drifting of sub-pulses & glitch phenomena would be easier with high time resolution of SKA. Moreover, higher sensitivity would also allow for detection of faint emission (if any) during the null itself. **b)** The SKA, with its high sensitivity and possible gating in 100 bins across the pulsar period would be ideal for carrying out (much awaited) off-pulse emission searches and studies. **c)** Although several mechanisms have been proposed for the observed giant pulse (GP) emission, there is no satisfactory answer. Large bandwidths are required to separate intrinsic frequency structure from that imposed by propagation through the interstellar medium, The increased sensitivity facilitated by SKA will help in detection and study of micro-structures as well as giant pulses from a statistically large number of pulsars. **d)** The SKA is expected to greatly help us understand the 3D structure of pulsar emission beams currently described by a number of models [229, 245, 190, 236]. On the other hand, it would help constrain the models for the polarisation characteristics of a pulsar profile that have been developed in recent times [224, 223, 225]. **e)** The study of the motion of the emission point, requiring nano- or pico-arcsecond imaging, would become possible with the SKA. This would be important in understanding the difference in emission between an ordinary pulsar and a millisecond one.

Equation of State - The measurement of the spin-orbit effect leads to the determination of moment of inertia of a pulsar in a double pulsar system [259, 250] and can be done easily with the high precision timing technique 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 (review by [174]) which can also be used to constrain the EoS. 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 [259].

Gravitational Physics - Two key Science goals of the SKA involve exploring the nature of relativistic gravity and to directly detect nano-Hertz gravitational waves. Neutron stars in binary systems are extremely successful in testing general relativity in the strong field regime [254, 255, 222, 256, 241, 217, 250]. On the gravitational wave aspect, Indian community plans to pursue investigations that can provide constructs, relevant for analysis of pulsar timing array data, that model gravitational waves from massive spinning black hole binaries in post-Newtonian eccentric (and hyperbolic) orbits [178, 258, 192, 180]. Preliminary tests for InPTA with regular monitoring of a number of pulsars is already underway (discussed earlier). 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.

6.7 Indian Community

At present, there exists a sizeable community in India, working on various aspects of NS physics. There are about $\sim$20 *senior scientists*, $\sim$40 *post-doctoral fellows* and $\sim$20 *graduate students* working in more than twenty research institutes and university departments. The main agenda of this community, envisaged for the near future, are the development of - **(a)** key science projects (discussed before), **(b)** appropriate technology and **(c)** human & other resources. The technology development would have to be done on three fronts, namely - **i)** *software development*, **ii)** *hardware acquisition* and **iii)** *enhanced storage capability.*

Chapter 7

MASSIVE STARS AND THEIR INTERACTION WITH INTERSTELLAR MEDIUM

P. Manoj, S. Vig, A. Tej, U. S. Kamath, M. Gopinathan

7.1 Scientific Background of the topic

High-mass stars (M $\geq 8M_{\odot}$), 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 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 the processes involved are completely different. The current theoretical and observational status of high-mass star formation can be found in Tan et al. (2014). Observationally, factors that hinder the investigation of massive stars in their infancy include 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 (Zinnecker & Yorke, 2007). 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. This is a vast topic covering many aspects but our focus is towards understanding (i) the early phases, and (ii) feedback of young massive stars.

Early Phases of Massive Stars

The early phases of massive stars are characterized by the presence of cold clumps detected in millimeter and infrared wavebands, water or methanol maser, and compact, faint radio emission signaling the onset of ionization (Molinari et al., 2008; S´anchez-Monge et al., 2013). In the earliest phases, high-mass stars are associated with small and dense HII regions known as ultra-compact HII (UCHII) regions and the recently identified class of hyper-compact HII (HCHII) regions. The lack of detailed kinematics across HII regions (hypercompact, ultracompact and compact) severely hinders the understanding of these early phases. Observationally, two scenarios unfold (i) the elongated ionised gas is seen perpendicular to the outflow and coincides with the location of a dusty disk, e.g S140 IRS1 (Hoare, 2006; Maud et al., 2013), and (ii) the elongated ionized gas represents a radio jet and is perpendicular to the disk structure such as GGD27 (Marti et al., 1993; Carrasco-Gonz´alez et al., 2012). It is not clear what distinguishes these two classes of massive young stellar objects and whether they simply represent stages of an evolutionary chronology.

Triggered Star Formation

Star formation is a self-regulatory process and feedback from massive stars can have contrasting effects on the surrounding ISM. While they can inhibit further formation of stars by destroying the natal cloud through powerful stellar wind and ionizing radiation, the energy input is also seen to trigger subsequent star formation in the parental cloud (Elmegreen, 1998; Zinnecker & Yorke, 2007). The two commonly accepted models for this are the collect and collapse ((CC) Weaver et al., 1977; Deharveng et al., 2010, and references therein) and radiatively driven implosion ((RDI) Lefloch & Lazareff, 1994). The preferred mechanism (CC or RDI) and the link with the initial star formation is still unclear. An interesting manifestation of the interplay between massive stars and the surrounding ISM is seen in the form of bubbles which are observed as bright-rimmed shells prominent in the mid-infrared. These bubbles are believed to be formed around massive star(s) as is evident from the high correlation seen between IR bubbles and HII regions (Churchwell et al., 2006, 2007; Deharveng et al., 2010). The formation of these bubbles is due to various feedback mechanisms like thermal overpressure, powerful stellar winds, radiation pressure, or a combination of all of them (Churchwell et al. 2006; Deharveng et al. 2010; Simpson et al. 2012). Fragmented dust shells or clumps have been observed at the borders of several IR bubbles (Zavagno et al., 2010; Ji et al., 2012; Liu et al., 2016). Populations of young stellar objects (YSOs) are also seen towards the periphery of several bubbles (Deharveng et al., 2010) thus qualifying these objects as suitable laboratories to probe triggered star formation.

7.2 Outstanding Science Problems and Role of SKA

1. ***Earliest evolutionary chronology of the first HCHII regions:*** Does the ionisation first prevail along the disk or does it occur along the jet of the protostar? This question requisites an answer. Considering that massive stars have short evolutionary timescales (~ 10^5 yrs), these protostellar phases are not expected to last long. Hence, sensitive surveys to identify and isolate these objects to extend the existing sample, will go a long way in enhancing our understanding of the earliest phases. SKA with its multi-frequency and multi-scale capabilities should help address this issue. It is expected that with the sensitivity of SKA (~ 0.1 μJy at 10 GHz for 10 min integration), HCHII regions formed around stars of type B1 and earlier should be sampled throughout our Galaxy. In addition, the Core Accretion model for massive star formation predicts that the outflow is the first structure to be ionised by the protostar with a flux density of ~ $(20-200) \times (\nu/10\ \mathrm{GHz})^p$ mJy for a source at a distance of 1 kpc with a spectral index p = 0.4−0.7, with an apparent size that is typically ~ 500 AU at 10 GHz (Tanaka et al., 2016). It should be possible to substantiate this with SKA using multiple frequencies given that at a distance of 1 kpc, SKA should be able to resolve spatial scales upto ~ 50 AU at 10 GHz (corresponding to a resolution of 0.05" for the largest baseline of 150 km). This should allow us to distinguish between competing models regarding the nature of ionised gas emission, i.e whether it is arising due to thermally evaporating flow from disks (Lugo et al., 2004) or gravitationally trapped ionised accretion flow (Keto, 2002). The sensitivity and resolution expected from SKA for radio emission from HII regions around massive stars are demonstrated through Figure 1. This is compared with the values currently achievable using uGMRT.

2. ***Dynamics of ionised gas emission in the earliest HCHII regions:*** In order to understand the dynamics of ionized gas, it is essential to obtain high angular resolution (one tenths to one-hundredth of an arcsec) mapping of the RRLs. Usually, the RRL line flux being an order or two lower in magnitude than the continuum flux, such a study often becomes prohibitively expensive in time. With the unprecedented collecting area of SKA and large frequency coverage, it will be feasible to carry out such multi-frequency measurements at spatial scales that resolve the HCHII regions, enabling precise kinematics that appear challenging with the currently available facilities. For instance, the SKA1-mid bands cover nearly 200 hydrogen RRLs, from H265α to H78α and H334β to H45β. Taking advantage of the antenna configurations, multiple frequency maps at the same scale (resolution) can be obtained to understand the motion of the ionised gas.

3. ***Genesis of HII region morphology at multiple scales:*** UCHII regions display a wide variety of radio morphologies such as cometary, bipolar, shell, irregular, core-halo (Churchwell, 2002). The morphology of a HII region is significant as it can provide vital clues about density inhomogeneities in the molecular cloud, the age, as well as the dynamics of the ionized and molecular gas. However, classification based on interferometric measurements could be biased by the limited range of spatial scales that the observations are sensitive to. A complete mapping of HII regions at all scales is expected to eliminate problems associated with the morphological classification. Therefore, a complete continuum picture of the HII region will be revealed by multi-configuration observations, which SKA is expected

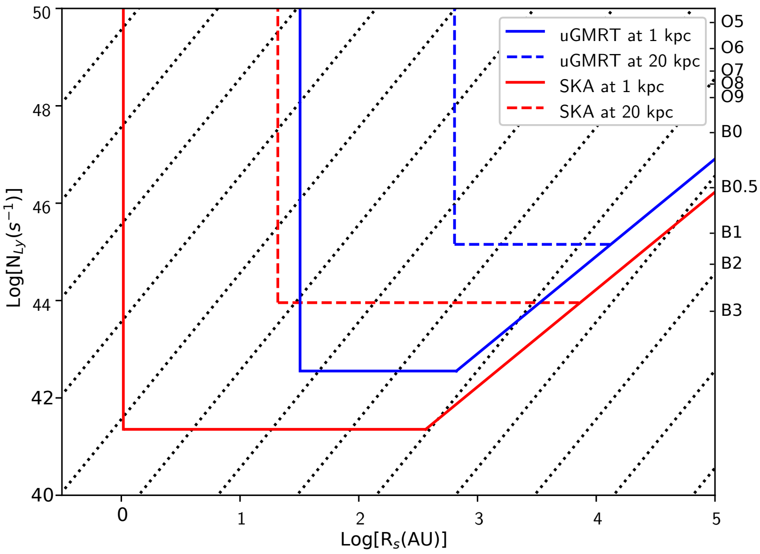

Figure 7.1: This figure is adapted from Fig. 1 of Umana et al. (2014) and shows the detection limit achievable with SKA in comparison with uGMRT. The plots show the flux density of a homogenous, isothermal HII region as a function of the Stromgren radius and the Lyman continuum photon flux of the ionizing star. For SKA we consider the frequency of 9GHz, 3σ of 2.4μJy and resolution of 1 arcsec and for uGMRT these values are 1.28GHz, 46μJy, and 2 arcsec, respectively. For both configuration the on source observation time is assumed to be 10mins. The solid curve corresponds to a distance of 1kpc and dashed curve corresponds to a distance of 20kpc, respectively. The dotted line corresponds to HII region density, from bottom right 10^{-1} cm^{-3} to top left 10^{11} cm^{-3} with a step of 10.

to provide. In addition, with SKA observations we foresee a clarity regarding the hierarchical density and temperature structures that manifest as the association of the large-scale diffuse emission with the compact HII regions embedded within them (Kurtz et al., 1999; Kim & Koo, 2001; Shabala et al., 2006).

4. ***Bubbles and Triggered Star formation:*** *B* ubbles provide an ideal database not only for probing high-mass star formation but also for addressing issues related to triggered star formation. Detecting the onset of ionization in the form of resolved HCHII regions is challenging given their small sizes and large opacities in the radio frequencies. With the achievable high resolution and sensitivity (Umana et al., 2014), SKA has the potential to enable the detection of the early phases of massive star formation triggered by the expanding bubble using the frequency coverage offered. There is growing evidence of arc-type structures seen in the infrared in the bubble interiors (Das et al. 2016 and references therein). Ochsendorf et al. (2014) carried out two-dimensional hydrodynamical simulations to understand the formation of these structures and proposed the bow or dust-wave scenario. Here, a rupture in the bubble rim and/or an existing density gradient allows the ionized gas to flow towards low-density regions dragging the dust along which is then halted in the flow direction by the radiation pressure of the massive young star resulting in a bow or dust-wave. Detailed kinematics of the ionized gas in the bubble (the ruptured or broken one) interiors would shed light on observational and theoretical aspects of these arc-type features. And SKA has the potential to address this.

7.3 Contributions by the Indian Community and Current work underway

The Indian Star Formation community has been trying to address various aspects of high-mass star formation through multiwavelength investigations of specific star forming regions. Indian astronomers have been using facilities such as the Giant Metrewave Radio Telescope (GMRT), India and the Very Large Array (VLA), USA. Here, we discuss a few diverse results obtained. The radio morphology of the star-forming region IRAS 19111+1048 investigated by Vig et al. (2006) showed the presence of a highly inhomogeneous ionized medium in the neighbourhood of an UCHII region. Twenty compact sources including one non-thermal source were identified. The radio spectral types for majority of the compact sources match with the spectral type of the near-infrared counterparts. However, not all compact radio sources are internally excited by an embedded ZAMS star. In cases such as IRAS 17258-3637 (Vig et al. 2014) and IRAS 06055+2039 (Tej et al. 2006), apart from the brightest compact source that represents the location of exciting star(s), several high density radio clumps have been detected that are likely to be externally ionized in a clumpy medium. Studies of young clusters in HII regions (Mallick et al. 2015) and sites of triggered star formation associated with expanding HII regions (Samal et al. 2014) have also been investigated using GMRT. Spectral indices of diffuse emission, suggesting non-thermal emission and extending up to 3 pc, have been determined towards the cometary HII region IRAS 17256-3631 at low frequencies (Veena et al. 2016). In addition, the kinematics of this HII region has been investigated using Radio Recombination Lines (RRLs) from GMRT (Veena et al. 2017). The study of a young embedded (proto) cluster has been carried out by Vig et al. (2007, 2017) in order to understand the environment of massive protostars. Vig et al. (2018) have attempted to understand the nature and source of radio emission associated with a massive protostellar candidate that is responsible for one of the most powerful jets seen among massive protostars. In addition, recent works by Das et al. (2016, 2017) have studied in detail few southern IR bubbles. GMRT observations have helped identifying the ionized gas flow responsible for the mid-infrared arc seen close to the location of the exciting star in the bubble S10 (Das et al. 2016). In bubble CS51 (Das et al. 2017), low-frequency GMRT observations reveal the presence of three compact emission components apart from large-scale diffuse emission within the bubble interior. Radio spectral index map further shows the co-existence of thermal and non-thermal emission components. GMRT maps combined with Herschel far-infrared maps suggest the champagne-flow model as the likely mechanism for the cometary morphologies of the ionized gas in the southern HII regions G346.056−0.021 and G346.077−0.056 (Das et al. 2018). Nandakumar et al. (2016) have discussed the HII region complex associated with IRAS 17160-3707 that hosts the bubble CS-112. This non-thermal emission perceived at the periphery of the bubble is attributed to the presence of relativistic electrons in shocked regions of gas along the bubble boundary. Ramachandran et al. (2017) examined the cometary HII associated with IRAS 20286+4105 and proposed an alternate picture of a supernova and a runaway star responsible for the HII region.

7.4 Anticipated results

Most of the problems discussed above have no clear answers and models have been proposed to speculate answers. It is expected that with SKA, the study of massive star formation and triggering of star formation in the vicinity studies can be carried out by extending the current studies to scales and levels that may answer as well as question our current understanding of the formation of massive stars and their interaction with the ISM.

7.5 The approximate number of persons, (mainly permanent faculty members) currently active in India, in this area.

Apart from the proposers, there are approximately 10 faculty members who are working in the area of massive star formation.

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Chapter 8

Budget

There are some basic requirements to further expand and sustain the activities in the SWGs as well as to meaningfully contribute to towards this effort. The nature of the requirement is spread across cutting edge computing resource, fellowships/salaries for pre-doctoral and post-doctoral researchers as well as support to organize conferences/workshops and travel to international conferences to present the work done under the common scientific theme of the group. The budget presented here is based on requirements from all the SWGs, and does not include the computing resource requirements (which will be included in the Data Centre chapter).

As scientists, it is important that the continuum survey community of SKA−India shares their research findings with astronomers as well as non-astronomers to increase the visibility of research and provide interested individuals with more information. This will help develop the expertise needed to carry out research in meaningful ways and an opportunity to learn valuable information from people working with similar science goals or techniques. In order to present our research findings during its many stages at international meetings and conferences, we request for an appropriate allocation of funds. It assumed that, for Foreign Travel, the community will need about 40 trips per year of 2L each.

It is obvious that the development of human resource is the most important task ahead. The community has already started working on two aspects – training younger generation and sharing of knowledge. To achieve this, it is envisaged that the groups will require to hire people at different levels, Postdoctoral Fellows (PDFs), Research Scholars (JRFs/SRFs) and Project Assistants. The corresponding salaries are computed assuming we need 24 PDFs (40K p.m. for five years), 14 JRF/SRFs (30K p.m. for five years), 5 Project Assistants (60K p.m. for five years).

No	Object Heads	Estimated Cost (in Crore)	FE Component (in Crore)
1	Salaries (PDF, JRF/SRF, Project Assistant)	10.0	0
2	Domestic Travel / Meetings / Conferences / Schools	2.0	0
3	Foreign Travel	4.0	0
	Total	16.0	0

Chapter 9

List of all institutions from which the authors have contributed to the write up

The report contains contribution from members working in the following institutions (the SKAIC member institutions are highlighted in italics):

- **Delhi:**
  1. Department of Physics and Astrophysics, University of Delhi, Delhi
  2. *Jamia Millia Islamia Central University, New Delhi*
- **Goa:**
  3. *Birla Institute of Technology and Science (BITS) Pilani, KK Birla Goa Campus*
- **Gujarat:**
  4. *Physical Research Laboratory (PRL), Ahmedabad*
- **Karnataka:**
  5. *Indian Institute of Astrophysics (IIA), Bangalore*
  6. *Indian Institute of Science (IISc), Bangalore*
  7. MCNS, Manipal Academy of Higher Education, Manipal
  8. *Raman Research Institute (RRI), Bangalore*
- **Kerala:**
  9. Indian Institute of Science Education and Research (IISER), Thiruvananthapuram
  10. *Indian Institute of Space Science & Technology (IIST), Thiruvananthapuram*
- **Madhya Pradesh:**
  11. *Indian Institute of Technology (IIT), Indore*
- **Maharashtra:**
  12. Centre for Excellence in Basic Sciences (CEBS), Mumbai
  13. *Department of Physics, S P Pune University, Pune*
  14. Homi Bhabha Centre for Science Education (HBCSE), TIFR, Mumbai
  15. *Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune*

16. *National Centre for Radio Astrophysics (NCRA), TIFR, Pune*
17. *Tata Institute of Fundamental Research (TIFR), Mumbai*

- **Odisha:**

18. National Institute of Science Education and Research (NISER), Bhubaneswar

- **Punjab:**

19. *Indian Institute of Science Education and Research (IISER), Mohali*

- **Rajasthan:**

20. Birla Institute of Technology and Science (BITS) Pilani, Pilani Campus

- **Tamil Nadu:**

21. Chennai Mathematical Institute (CMI), Siruseri
22. Indian Institute of Technology (IIT), Chennai
23. Institute of Mathematical Sciences (IMSc), Chennai

- **Telangana:**

24. Birla Institute of Technology and Science (BITS) Pilani, Hyderabad Campus

- **Uttarakhand:**

25. Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital

- **Uttar Pradesh:**

26. Amity Institute of Applied Sciences, Amity University, Noida
27. Indian Institute of Technology (IIT), BHU, Varanasi
28. *Indian Institute of Technology (IIT), Kanpur*

- **West Bengal:**

29. *Indian Institute of Technology (IIT), Kharagpur*
30. *Indian Statistical Institute(ISI), Kolkata*
31. Jadavpur University, Kolkata
32. *Presidency University, Kolkata*
33. *Saha Institute of Nuclear Physics (SINP), Kolkata*
34. Surendranath College, Calcutta University, Kolkata

- **Other institutions (representing people who were PhD students in India working on SKA-related topics and are currently holding temporary positions abroad):**

35. Asia Pacific Center for Theoretical Physics, Pohang, Korea
36. ASTRON, Netherlands Institute for Radio Astronomy, The Netherlands
37. Imperial College, London, U. K
38. Max Planck Institute for Gravitational Physics, Potsdam-Golm, Germany
39. Stockholm University, Stockholm, Sweden
40. Universidad Nacional Autonoma de Mexico, Mexico
41. University of Sussex, Brighton, UK
42. University of the Western Cape and SKA, Cape Town, South Africa