SKA-India Science Book: Version 1

February 16, 2015

Contents

Introduction to the SKA-India Science Working Groups

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The Square Kilometre Array (SKA), the next generation radio telescope, has now entered the design stage for SKA phase-I, that will run till 2016-2017, after which SKA-I construction will start towards the end of 2017. Early science is expected to be possible from around 2020-21 or so. The SKA is a truly international telescope, with India being one of the eleven member countries in the SKA Organization currently involved in the design of the SKA-I. At present, India is leading one of the ten technical design work packages for SKA-I, that are coordinated by the SKA Office (SKAO). Furthermore, India is also looking to enhance its scientific contribution to the SKA, and to build up a suitable base of astronomers that will be ready to use the SKA when it is ready.

The capabilities of SKA-I will be phenomenal, for a variety of science goals and applications, and will far surpass that of any existing or planned radio astronomy facility. The goals cover a wide range of research areas starting from understanding the formation of stars using hyperfine transition of neutral hydrogen to testing Einstein's theory of general relativity using pulsars to detailed understanding of some of the early phases in the life of the Universe. In order to achieve these science results, the SKA has already formed a number of international science working groups (SWGs) which provide input to the SKAO on issues relating to the design, construction, and future operations of the SKA, in addition to sharpening the focus and understanding of the science goals.

With a view to promoting activities related to SKA science in India, during the last Astronomical Society of India (ASI) meeting at IISER Mohali, a one-day workshop on "Science with the SKA" was organised on 19 March 2014. One of the major outcomes of this workshop was the formation of SWGs in India. These groups are expected to facilitate SKA-relevant scientific discussions within the Indian community, interact with the international SWGs of the SKA, organise training schools within India to get more people involved in SKA-related science and so on. These SWGs represent the following areas: (i) Epoch of Reionization and Cosmology, (ii) Radio Transients, (iii) Pulsars, (iv) Cosmic Magnetism and Turbulence, (v) Continuum Surveys, (vi) HI and Galaxy Evolution, and (vii) Solar and Heliospheric Physics.

Over the last one year or so, these SWGs have been involved in preparing documents in their respective areas with the aim of listing the science activities which could possibly be taken up by the Indian astronomy (and physics) community. This booklet is a first collection of these articles. We have not made any attempt to make the articles uniform in any sense, so the reader may find the emphasis of each article to be somewhat different from the others. Nevertheless, we hope these will serve as a good introduction and direction finder to anyone who may be interested in getting involved with the SWGs. The contents of these documents will be presented in the workshop on "Indian Participation in the SKA" to be held in NCRA-TIFR, Pune on February 16, 2015 as part of this year's ASI meeting.

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As the next step, we plan to expand and refine these articles, with the aim to possibly publish them in an Indian journal as proceedings of the workshop. These would help the Indian astronomers realise as to what kind of SKA-related research projects they can take up in the near future. These could range from theoretical studies on the science to be done by the SKA-I, to simulations for better understanding of what will be detectable by the SKA-I – signals, foregrounds etc, to prototype observations with existing radio telescopes which can serve as test cases for preparing for the SKA-I.

We would like to thank all colleagues who have contributed their time and effort enthusiastically to this collection of articles, and look forward to continued and increased participation from the Indian astronomy community in these endeavours.

SKA-India Science Working Group on Epoch of Reionization and Cosmology

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1 Introduction

The studies of the epoch of reionization and cosmology are among the primary science goals of the Square Kilometre Array (SKA) radio telescope[1].Usually the era between redshifts $6 \lesssim z \lesssim 15$ is known as the epoch of reionization when the neutral hydrogen was gradually ionized by the first stars. One is interested in probing this phase to understand the formation of first stars and constrain the physics of early galaxy formation. The radio telescopes attempt to detect the 21 cm hyperfine transition line of neutral hydrogen (HI) arising from the reionization epoch. In contrast, the studies related to cosmology using radio telescopes are focussed on the post-reionization epoch $z \lesssim 6$, by detecting either the 21 cm radiation of HI or the continuum radiation from galaxies.

The Indian science community has always been interested in studies of cosmology, and more recently on reionization. Though most of the work has been concentrated on theoretical calculations, there have been some interests in observations too. The observations were primarily driven by the low-frequency radio telescopes operating in India, namely the Giant Metrewave Radio Telescope[2] (GMRT; recently upgraded to uGMRT, now formally a SKA pathfinder) and the Ooty WideField Array (OWFA, formerly known as the ORT[3]). In addition, there have been efforts in measuring the all-sky cosmic radio spectrum using the instrument named SARAS (Patra et al., 2013).

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The international science groups of the SKA have already outlined a number of science cases relevant to these areas[4]. This article outlines the past activities in related areas within India, and also discusses possible areas where Indian scientists can potentially contribute to the SKA science.

2 Epoch of reionization

The epoch of reionization is quite an important landmark in the evolution of the universe as it corresponds to a major phase change of the baryonic matter (for reviews, see Barkana and Loeb, 2001; Choudhury and Ferrara, 2006a; Choudhury, 2009). Most of the observational constraints on reionization come from the Cosmic Microwave Background Radiation (CMBR) temperature and polarization anisotropies and the quasar absorption spectra at $z \gtrsim 6$ (Choudhury and Ferrara, 2005, 2006b; Mitra et al., 2011, 2012). Probing the ionization state of hydrogen at $z > 7$ using spectra of distant sources is a great challenge as the number of detectable quasars and galaxies decreases significantly at high redshifts. The possibility of detecting the hyperfine transition of HI thus presents a promising probe of this epoch.

The rest frame frequency of the HI hyperfine transition is at 1420 MHz. The signal from HI at high redshifts will be observed at a lower frequency $\nu_{\rm obs} = 1420/(1+z)$ MHz, which is accessible to low-frequency radio instruments such as LOFAR, MWA and uGMRT. The SKA-low is being planned to operate at frequencies relevant to the reionization epoch, i.e., $\nu_{\rm obs} \sim 50 - 350$ MHz, which corresponds to 21 cm observations at $z \sim 3 - 30$.

The 21 cm signal is observed against the background of the CMBR. The main quantity of interest is the differential brightness temperature of the 21 cm radiation with respect to the CMBR:

$$\begin{aligned} \delta T_b(\nu_{\rm obs}, \hat{\mathbf{n}}) &\equiv \delta T_b(\mathbf{x}) \\ &= 27\ x_{\rm HI}(z, \mathbf{x})[1 + \delta_{\rm B}(z, \mathbf{x})] \left(\frac{\Omega_{\rm B} h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_{\rm CMB}(z)}{T_{\rm S}(z, \mathbf{x})}\right] \text{mK}, \end{aligned} \tag{1}$$

where $\nu_{\rm obs}$ is the frequency of observation, $\hat{\mathbf{n}}$ is the direction of observation on the sky, $\mathbf{x} = r_z \hat{\mathbf{n}}$ and $1 + z = 1420\ \text{MHz}/\nu_{\rm obs}$, with r_z being the comoving radial distance to redshift z. The quantities $x_{\rm HI}(z, \mathbf{x})$ and $\delta_{\rm B}(z, \mathbf{x})$ denote the neutral hydrogen fraction and the density contrast in baryons respectively at point $\mathbf{x}$ at a redshift z. The CMBR temperature at a redshift z is denoted by $T_{\rm CMB}(z) = 2.73\ \times(1 + z)$ K and $T_{\rm S}$ is the spin temperature of neutral hydrogen. The spin temperature $T_{\rm S}$ is determined by the coupling of neutral hydrogen gas with CMBR photons by Thomson scattering, Lyα coupling and collisional coupling. Considering all these coupling effects, the spin temperature can be written in the following form

$$T_{\rm S}^{-1} = \frac{T_{\rm CMB}^{-1} + x_\alpha T_\alpha^{-1} + x_c T_{\rm K}^{-1}}{1 + x_\alpha + x_c}, \tag{2}$$

where $T_{\rm K}$ is the kinetic temperature of the gas and T_α is the colour temperature of the Lyα photons which, in most cases of interest, is coupled to $T_{\rm K}$ by recoil during repeated scattering. The quantities x_c and x_α are the coupling coefficients due to collisions and Lyα scattering, respectively.

Observations of the redshifted 21 cm radiation at a specific frequency can be mapped to a redshift and thus to a position along the line of sight. In absence of the peculiar velocities of

[4] `http://astronomers.skatelescope.org/wp-content/uploads/2014/10/SKA-TEL-SKO-0000122-SCI-REQ-RE-01-SKA1SciencePrioritiesOutcome.pdf`

HI gas, 21 cm radiation is redshifted only due to the expansion of the universe. The redshift will be modified in presence of the peculiar velocities of HI gas. As gas tends to move toward overdense regions, over/underdense regions will appear more over/underdense at large scales. This changes the strength of the observed 21 cm power spectrum and makes it anisotropic. If the line of sight is taken to be along the x-axis, the position $\mathbf{s}$ of a element in redshift space coordinate will be given by,

$$s_x^i = x^i + \frac{v_x^i(1+z_{\rm obs})}{H(z_{\rm obs})}, s_y^i = y^i, s_z^i = z^i \tag{3}$$

where $z_{\rm obs} = (1+z_{\rm cos})(1-v_x^i/c)^{-1} - 1$ is the observed redshift and $z_{\rm cos}$ is the cosmological redshift. Once this mapping from $\mathbf{x} \to \mathbf{s}$ is established, one can compute the 21 cm signal in the redshift space.

The planned observations of the 21 cm signal can be broadly divided into two classes: the first would be to find the evolution of globally averaged signal, and the second would be to detect the fluctuations in the signal. Radio interferometers like the SKA would concentrate on detecting the fluctuations in the signal, e.g., quantities like the power spectrum $P(\mathbf{k})$ defined as

$$\langle \delta\hat{T}_b(\mathbf{k}) \delta\hat{T}_b^{\star}(\mathbf{k}') \rangle = (2\pi)^3 \delta_D(\mathbf{k}-\mathbf{k}') P(\mathbf{k}), \tag{4}$$

where $\delta\hat{T}_b(\mathbf{k})$ is the Fourier transform of $\delta T_b(\mathbf{x})$ defined in equation (1).

The radio telescopes essentially measure the visibility $V(\mathbf{U}, \nu_{\rm obs})$ which nothing but the two-dimensional Fourier transform of the sky signal, i.e.,

$$V(\mathbf{U}, \nu_{\rm obs}) \propto \int {\rm d}^2 n \ {\rm e}^{-2\pi {\rm i} \mathbf{U}\cdot\hat{\mathbf{n}}} \ \delta T_b(\nu_{\rm obs}, \hat{\mathbf{n}}), \tag{5}$$

where $\mathbf{U}$ is a two-dimensional vector denoting the baseline. We have ignored the effect of the antenna beam pattern in the above expression.

2.1 Theoretical models: semi-analytical

Modelling the 21 cm signal from the reionization epoch is not straightforward. The signal depends on the properties of the galaxies at high redshift which are largely unknown. In addition, solving the transfer of radiation in the IGM is quite challenging. The full physics can only be dealt by numerical simulations which, however, require large computational resources. An alternate way is to explore analytical models where complex physical processes are approximated by introducing parameters, and then the space of these unknown parameters are thoroughly explored.

Analytical calculations involving fluctuations in T_S and the HI density field during the dark ages (i.e., before the first stars were formed) were explored by Bharadwaj and Ali (2004). The effect of peculiar velocities was included in the analysis to the linear order. Later these calculations were extended to other epochs including the reionization. The reionization was modelled by assuming that the ionization field is composed of non-overlapping ionized bubbles of a fixed size (Bharadwaj and Ali, 2005). The visibility correlation

$$\langle V(\mathbf{U},\nu) V^*(\mathbf{U},\nu+\Delta\nu) \rangle \propto \int_0^\infty {\rm d}k_\parallel \ P(\mathbf{k}) \ \cos(k_\parallel \Delta r), \quad k = \sqrt{k_\parallel^2 + \frac{4\pi^2 U^2}{r_z^2}}, \quad \Delta r = \frac{\partial r_z}{\partial \nu} \Delta\nu, \tag{6}$$

which essentially probes the power spectrum at Fourier modes $k \geq (2\pi/r_z)U$, was proposed to be a useful quantity for detecting the cosmological signal. The correlation decreases as $\Delta\nu$ increases for redshifted 21 cm signal from cosmological HI, hence this frequency decorrelation can help in distinguishing it from continuum foreground sources. The properties of the multifrequency angular power spectrum $C_\ell(\Delta\nu)$, which is identical to the visibility correlation in the flat-sky approximation with $\ell = 2\pi U$, was studied in detail by Datta et al. (2007b).

The ionized bubbles during the epoch of reionization will introduce non-gaussian signatures in the brightness temperature field even if the underlying density field is gaussian. The possibility of detecting these non-gaussianities was explored by measuring the bispectrum of HI fluctuations (Bharadwaj and Pandey, 2005; Saiyad Ali et al., 2006). The anisotropies in the signal, arising from peculiar velocities and the Alcock-Paczynski effect, can be used for constraining cosmological parameters (Ali et al., 2005).

The distribution of ionized bubbles can be modelled analytically based on the excursion set formalism. An improved model has been developed by Paranjape and Choudhury (2014) accounts for the fact that (a) the steps of the random walks are correlated by including a realistic smoothing filter and (b) dark matter haloes preferentially form near peaks in the initial density field. The results are found to have a significant impact on estimates of the observable HI power spectrum.

Most of the calculations were calculated in the flat-sky approximation where one can drop the so-called w-term from the visibility analysis. However, for large field of view, this approximation is not valid any more. The effect of the w-term, arising from large fields of view, on power spectrum calculations has been explored and quantified by Dutta et al. (2010).

Since reionization is driven by stars within the first galaxies, it is natural that the reionization history is sensitive to matter fluctuations that collapse and form structures first. It is found that any parameter or process that affects the matter power spectrum at small scales can be constrained by reionization. Warm dark matter can suppress the power at small scales (below the free streaming length) and hence can delay structure formation. There have been some studies of (alternate) models of dark matter, similar to warm dark matter, which can impact the formation of first stars (Das and Weiner, 2011). Interestingly one can constrain the mass of warm dark matter particles using reionization observations (Dayal et al., 2015).

Similarly, presence of a primordial magnetic field can boost the power at small scales. The global HI signal and the fluctuations in presence of a primordial magnetic field has been studied by Sethi and Subramanian (2009) who concluded that the SKA should be able to detect magnetic field-induced signal for a wide range of magnetic field values, in an integration time of one week. Vasiliev and Sethi (2014) have studied the impact of primordial magnetic fields on the HI absorption from the epoch of reionization. Pandey et al. (2014) have put constraints on the amplitude of such magnetic fields using reionization models and relevant observations.

Besides HI, there have been studies exploring the possibility of using the hyperfine transition of $3He^+$ as a probe of the intergalactic medium (Bagla and Loeb, 2009). The emission signal from ionized regions during reionization is expected to be anti-correlated with 21 cm maps.

While most of the calculations discussed above are fairly generic and can be applied to any instrument of interest, it would be worth exploring them for making predictions relevant for SKA-I. It would also be interesting to explore how to interpret the data expected from the SKA and understand the physical processes relevant for reionization.

2.2 Theoretical models: simulations

The complexities of galaxy formation and radiative transfer at high redshifts demand usage of full numerical simulations to understand the distribution of ionized hydrogen. However, such simulations are quite demanding in terms of computational power and hence are slow. An alternate way is to use semi-numerical calculations. A particular version of such simulations is based on generating the large-scale density field and identify the locations of haloes (galaxies) through dark matter N-body simulations, and then use a excursion set motivated photon-counting method to generate the ionization field.

Choudhury et al. (2009) have used such a simulation to generate the inhomogeneous ionization field during reionization era. They also accounted for photon sinks (i.e., high density neutral regions) in their simulations, which was later improved by Choudhury et al. (2014). These semi-numerical calculations have been compared with full numerical simulations extensively by Majumdar et al. (2014), and they found a good agreement.

A typical 21 cm observation will span a wide range of frequencies along the line of sight, which would imply a observation volume spanning over a large redshift range. If the HI distribution evolves over such a redshift span, one needs to account for that effect in the simulations. Datta et al. (2012b, 2014) have studied this light cone effect and have shown that it can affect the power spectrum measurements.

The effect of peculiar velocities on the 21 cm signal have been studied extensively using numerical simulations (Shapiro et al., 2013; Jensen et al., 2013; Majumdar et al., 2013). These effects introduce anisotropies in the signal and also modify the amplitude of the spherically averaged power spectrum.

The effect of spin temperature fluctuations can play a major role at very early stages of reionization, i.e., the cosmic dawn. These inhomogeneities arise because of fluctuations in the Lyα radiation coupling and the gas temperature. Ghara et al. (2014) have used a simple radiative transfer model to study the effects of such fluctuations, along with the peculiar velocity effects.

All the above calculations are directed towards detecting the globally averaged statistical fluctuations in the ionization field. A different approach to detect the reionization epoch is to probe the ionized regions around individual luminous sources like quasars around $z \sim 7$. The detection possibilities using a matched filter technique, with effects of HI fluctuations and finite light travel time included, has been extensively explored by Datta et al. (2007a, 2008, 2009a,b); Majumdar et al. (2011); Datta et al. (2012a). These techniques can also be used for constraining the neutral hydrogen fraction in the IGM and the properties of the quasar (Majumdar et al., 2012).

Semi-numerical simulations have been used for estimating the effect of non-gaussianities (arising from the ionized bubbles) on the statistical errors on the HI power spectrum, which can be relevant for predicting the sensitivity of different instruments to measure the 21 cm power spectrum (Mondal et al., 2014).

The possibility of quantifying the angular power spectrum of the sky signal (which includes both the foregrounds and the 21 cm signal) from the visibilities is explored through two estimators (Choudhuri et al., 2014). The method has been validated using numerical simulations at 150 MHz.

2.3 Observations of the 21 cm signal at the reionization epoch

One of the GMRT frequency bands is centred around 153 MHz. This is ideally suited for probing HI at $z \sim 8.3$, well within the reionization epoch. It is well-known that the subtraction of foregrounds is one of the biggest challenges for 21 cm observations. The foregrounds include extragalactic point sources and synchrotron emission from our Galaxy. GMRT observations at 153 MHz has been used to characterise these foregrounds (Ali et al., 2008; Ghosh et al., 2012, 2013) which are relevant for studying the reionization epoch. Such observations can be very useful for 21 cm studies with the SKA.

3 Cosmology

It is believed that SKA can be quite competitive in probing cosmological parameters, even in the stage I (Maartens et al., 2015). The main goals in this area would be to complete all-sky HI intensity mapping surveys and also through all-sky radio continuum surveys in the post-reionization epoch. In addition, there would also be standard HI galaxy surveys. With SKA-2, it is believed that the status of cosmology will be revolutionized when a spectroscopic survey of ~ 1 billion galaxies would be completed.

Most of the studies within India have concentrated on the HI intensity mapping where it is not necessary to resolve and detect individual galaxies. The main quantity of interest has been the HI power spectrum which can be modelled as

$$P(\mathbf{k}) = \bar{x}_{\rm HI}^2 \, b^2(k) \, P_{\rm DM}(\mathbf{k}), \tag{7}$$

where $P_{\rm DM}(\mathbf{k})$ is the dark matter power spectrum (accounting for redshift space distortions arising from peculiar velocities), $\bar{x}_{\rm HI}$ is the neutral hydrogen fraction at the redshift of interest and $b(k)$ is the bias function of HI. The value of the bias will depend on how the HI is distributed within collapsed haloes (galaxies). At large scales $k \to 0$, it can be taken to be independent of k.

3.1 Theoretical studies for estimation of the 21 cm signal: analytical

Using HI within dense "clouds" (galaxies) to probe large-scale structures was proposed by Bharadwaj et al. (2001), which forms the basis for HI intensity mapping. The HI fluctuations can be studied using visibility correlations (Bharadwaj and Sethi, 2001), which is same as $C_\ell(\Delta\nu)$ in the flat-sky approximation. In this case, the system noise is uncorrelated across baselines and frequency channels which makes the calculations simpler. The corresponding values are estimated for the GMRT (Bharadwaj and Pandey, 2003). The possibility of constraining cosmological parameters using HI intensity mapping with a telescope similar to the GMRT was explored by Bharadwaj et al. (2009), and they concluded that the constraints can be at a precision comparable with supernova Ia observations and galaxy redshift surveys.

The latest theoretical and observational constraints on $\bar{x}_{\rm HI}$ and b was compiled by (Padmanabhan et al., 2015) which included constraints from galaxy surveys, HI intensity mapping experiments, damped Lyα system observations, theoretical prescriptions for assigning HI to dark matter haloes and the results of numerical simulations. These are helpful in quantifying the uncertainties in the signal as would be measured by future 21 cm experiments.

Since the amplitude of the 21 cm signal from cosmological HI is quite small, it makes sense to cross-correlate the measurements with other observations to detect it. The 21 cm signal, e.g., can be cross-correlated with Lyα forest of quasars which can be useful for probing cosmology (Guha Sarkar et al., 2011; Guha Sarkar and Datta, 2015), estimating cosmological distances using the BAO (Guha Sarkar and Bharadwaj, 2013) and also probing primordial non-gaussianities (Guha Sarkar and Hazra, 2013). There have also been some studies for cross-correlating the 21 cm signal with ISW signal from the CMBR (Guha Sarkar et al., 2009) and weak lensing of the CMBR (Guha Sarkar, 2010).

An interesting possibility is to use the gravitational lensing of the HI signal from distant galaxies (Saini et al., 2001) by clusters so that the flux is substantially magnified.

A gravitational-wave traversing the line of sight to a distant source produces a frequency shift which contributes to redshift space distortion. As a consequence, gravitational waves are imprinted as density fluctuations in redshift space. The possibility of detecting primordial gravitational waves using the redshift space HI power spectrum was considered by Bharadwaj and Guha Sarkar (2009), but was found to be difficult to detect.

3.2 Theoretical studies for estimation of the 21 cm signal: simulations

The possibility of using radio maps to study large-scale structure formation was explored by Bagla et al. (1997); Bagla (1999); Bagla and White (2003) who modelled the distribution using N-body simulations. Once the large-scale density field was generated in these simulations, the HI was assumed to be residing within high density regions. The detectability of the resulting signal by the GMRT was explored. These models were later improved by using more sophisticated prescriptions to model the HI distribution. The general assumption of these models was that the HI resides within collapsed haloes (Bagla and White, 2003; Bharadwaj and Srikant, 2004; Bagla et al., 2010; Khandai et al., 2011), with the fraction of HI being computed by normalising with respect to the observational constraints on $\bar{x}_{\rm HI}$. The signal has been estimated for existing telescopes like the GMRT by Bagla et al. (2010) where both visibility-based detection and radio maps were considered.

A similar study using SPH simulations has been done by Villaescusa-Navarro et al. (2014b) where the models have been calibrated with respect to existing observation of DLA column density distribution and the resulting signal has been computed for SKA-I. The same simulations have been used to explore the possibility of cross-correlating the 21 cm intensity maps with Lyman-break galaxy surveys in the post-reionization (Villaescusa-Navarro et al., 2014a).

The bias $b(k)$, which appears in expression for the HI power spectrum, is a parameter which is largely unknown. The possibility of constraining the large-scale HI bias using 21 cm observations in the post-reionization era has been explored using a Principal Component Analysis (Guha Sarkar et al., 2012).

3.3 Observations of the 21 cm signal

GMRT observations at a frequency of 610 MHz (Ghosh et al., 2011a) have been used for estimating the multi-frequency angular power spectrum $C_\ell(\Delta\nu)$, and a upper limit of $\bar{x}_{\rm HI} b_{\rm HI} < 2.9$ was established at $z = 1.32$ (Ghosh et al., 2011b). This rules out models with higher values of the parameter.

Sethi et al. (2013) have reported a possible detection of HI by cross-correlating GMRT observations with DEEP2 galaxy survey at $z \sim 1.3$.

The OWFA, which is currently being upgraded, would observe the sky at a frequency 326.5 MHz, which corresponds to 21 cm signal from $z = 3.35$. The possibility of detecting the redshifted 21 cm signal using the OWFA has been explored by Ali and Bharadwaj (2014).

3.4 Studies in cosmology relevant to the SKA

There have been a wide range of studies in cosmology within India which could possibly have some relevance for radio observations using the SKA. Though these calculations do not directly connect to 21 cm signal, it would be interesting to extend them keeping SKA-I in mind.

- Modelling of non-linear density and velocity fields is crucial for generating ionization maps in the reionization epoch. While N-body simulations are usually used for generating the full non-linear fields, they are not suited for probing the parameter space. Nadkarni-Ghosh and Chernoff (2013); Nadkarni-Ghosh (2013) have modelled the non-linear fields using analytical methods which can possibly be used for modelling the HI during reionization and post-reionization.

- One of the fundamental assumptions of the standard cosmological model is that the Universe is isotropic at large scales. Testing this assumption independently is quite crucial in establishing the standard model. There are indications that there exists a large scale anisotropy which can be probed by radio observations (Tiwari and Jain, 2015; Tiwari et al., 2015). The possibility that radio polarizations of distant galaxies are aligned on super-cluster or larger scales have also been explored in some details (Tiwari and Jain, 2013; Jain and Ralston, 1999). A large peculiar motion of the solar system with respect to the cosmological frame has been inferred from the dipole anisotropy in the sky brightness due to distant radio sources (Singal, 2011).

- Radio interferometry can be useful for measuring astronomical distances (Jain and Ralston, 2008).
- A model of dark matter, which affects the matter power spectrum at larger scales, can be constrained through surveys like SDSS and Lyα forest (Sarkar et al., 2014). A study of the non-linear clustering of matter in the Late Forming Dark Matter scenario in which dark matter results from the transition of non-minimally coupled scalar field from radiation to collisionless matter has been performed by Agarwal et al. (2014).
- There have been considerable amount of work on models of inflation and primordial non-gaussianities (Martin and Sriramkumar, 2012; Hazra et al., 2012, 2013; Sreenath et al., 2013; Martin et al., 2014; Sreenath and Sriramkumar, 2014; Sreenath et al., 2014). Constraining primordial non-gaussianities is expected to be one of the primary science goals of the SKA.
- Studies related to constraining dark energy models using large-scale structures, e.g., cluster number counts (Devi and Sen, 2011; Devi et al., 2013), can be extended to 21 cm studies as well.
- The galaxy luminosity function, in principle, contains information about the underlying matter fluctuations and hence can be used for constraining cosmological parameters (Jose et al., 2011). Such studies can be extended for 21 cm surveys as well.

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Transient Astronomy with Square Kilometer Array and its Precursors

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1 Introduction

Square kilometre Array (SKA) when ready will be world's largest radio telescope, to be built in Australia and S. Africa. It will be built in two phases. Phase I is expected to complete in 2020; Phase II will be completed in 2024. Phase I will have $\sim 10\%$ of the total collecting area. SKA will have a range of detectors: from aperture arrays to dishes; and will span the frequency range from a few tens of megahertz to a few gigahertz. SKA will have unique combination of great sensitivity, wide field of view and unprecedented computing power. Exploration of the transient Universe is an exciting and fast-emerging area within radio astronomy. With its wider field of view and higher sensitivity, the SKA, holds great potential to revolutionize this relatively new and exciting field, thereby opening up incredible new science avenues in astrophysics.

Transient radio sources are compact and usually the locations of explosive or dynamic events. The short-duration transients are powerful probes of intervening media owing to dispersion, scattering and Faraday rotation. The dynamic radio sky is poorly sampled as compared to sky in X-ray and γ-ray bands. This is because currently one can either obtain high time resolution but in quite narrow fields of view (FoVs). However, SKA will open up a new parameter space in the search for radio transients. For this reason transients are one of the major science goals of SKA, in addition to Astrobiology (The Cradle of Life), Galaxy Evolution – Continuum, Cosmic Magnetism, Cosmology, Epoch of Reionisation & the Cosmic Dawn , Galaxy Evolution – HI, and Pulsars ("Strong field tests of gravity").

Here it is important to note that multiwavelength observations of the sky are important for the detection and follow-up of transient sources, as they provide complementary views of the same phenomena. The SKA will be roughly contemporaneous with other International facilities like Large Synoptic Survey Telescope (LSST), Gaia, Thirty Meter Telescope (TMT) in optical/IR bands and next generation successors of Swift, Chandra and XMM-Newton in the gamma-ray and X-ray bands (such as SVOM (France-China), SMART-X (US) and ATHENA

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(ESA) missions). Therefore, multiwaveband observational efforts with wide fields of view will be the key to progress of transients astronomy from the middle 2020s offering unprecedented deep images and high spatial and spectral resolutions. Indian astronomers with wide-ranging experience of low frequency radio astronomy in a variety of astronomical phenomena and targets would be particularly well-placed to pursue time critical transient objects with SKA and observatories at other bands.

1.1 SKA, SKA precursors/pathfinders and timeline

There are several SKA pathfinder telescopes and the two SKA precursors. These will be very crucial in determining the capabilities of the final SKA. Some of these are:

1. Upgraded Karl G. Jansky Very Large Array (JVLA) with high sensitivity, continuous frequency coverage, flexible wideband correlator, and scaled array configuration.

2. Aperture Tiles In Focus (APERTIF), the new Phased Array Feed (PAF) receiver system for the Westerbork Synthesis Radio Telescope (WSRT) with quite large field of view (FOV).

3. Low Frequency Array (LOFAR), which is a pan- European radio phased-array telescope optimized for 30–80 MHz and the 110–240 MHz bands and spread over diameter of 100 km.

4. Australian SKA Pathfinder (ASKAP) is a new radio telescope t the Murchison Radio-astronomy Observatory (MRAO), Australia. ASKAP will have a FOV of 30 deg^2 and will work in rage 700–1800 MHz range.

5. The South African SKA pathfinder MeerKAT, which will have 64 13.5m dishes in Phase I, and 7 additional dishes in Phase II. . MeerKAT will support a wide range of observing modes, including deep continuum, polarisation and spectral line imaging, pulsar timing, and transient searches.

6. The Murchison Widefield Array (MWA), located at the Murchison Radio Observatory (MRO) site in Western Australia and was commissioned in June 2013. It observes in the 80-300 MHz bnand, has a FOV of about 1000 deg^2 at the centre of its observing range, and a centrally condensed foot-print of 3 km. The primary element of the array is a 4 $\times$ 4 array of dual polarisation dipoles and the array comprises 128 such *tiles*.

7. The upgraded Giant Metrewave Radio Telescope (uGMRT) has very recently acquired the status for SKA-pathfinder as well.

2 Radio Transients

Transient phenomenon usually represent extremes of gravitational and magnetic fields, velocity, temperature, pressure and density. Most often they have highly relativistic flows. In terms of duration, radio transients can be classified into two classes, long time variability (min-days) and bursting radio sky (msec-sec; Carilli 2014). Transients in radio bands are mainly dominated by three kinds of emission mechanisms:
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 etc. Incoherent transients are mostly discovered in the images of the sky.
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 (Thornton et al. 2013), pulsars, flare stars etc. The coherent emission transients are discovered in time series observations.
3:) **Thermal emission**: These kind of emission is seen in slow transients like novae, symbiotic stars.

2.1 SKA for transients

To search for transient phase space, one needs the combination of sensitivity, field of view and time on the sky. This has been difficult to realise simultaneously, hence there have been a very few comprehensive transient surveys in radio bands. In addition, the variation in time scales (nano seconds to minutes), and complex structures in frequency-time plane makes things further difficult. The advent of the multi-beam receivers placed on the single dish telescopes, such as Parkes and Arecibo has led us to detect new phenomena such as rotating radio transients (RRATs), Fast Radio Bursts (FRBs) etc. However, much larger FOV is required to discover more of such phenomena.

Some of the basic questions to ask in context of SKA are the following: What do we know about the radio transient sky? How can we improve searches for radio transients? What successes do we expect from SKA pathfinders? How will SKA pathfinders improve our understanding of transients?

To achieve the above goals, one needs the right combination of different technologies. Many of these technologies and ideas are being tested with the SKA pathfinders and precursors. The use of widely distributed many small elements for the SKA means that one needs to take advantage of vast computing resources to be able to sample a larger fraction of the sky. Also the discovery of truly transient events relies on having excellent instantaneous sensitivity. There is no point in integrating for longer on these objects to improve sensitivity, so one cannot therefore afford to trade integration time for field of view in this case.

SKA has adopted transients as its key science goal as it is well in tune with the concept of SKA which is "The primary success metric for the SKA Observatory will be the significance of its role in making fundamental scientific discoveries and facilitating overall scientific progress, expressed as high impact, peer-reviewed scientific papers using SKA data". 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). If SKA works in its full potential then it is expected to detect around 1 Tidal Disruption Event (TDE) per week at higher frequencies. SKA-MID and SKA-SURVEY will be ideal for this science. SKA-MID and SKA-SURVEY is also expected to detect around 1 FRB per day. LOFAR has recently detected a transient at 10 Jy flux density level at 60 MHz band (Stewart et al. 2015). The transient does not repeat and has no counterpart. The nature of this transient is enigmatic. SKA-LOW will most likely detect 100s of such transients per day in MHz band. Frail et al.(2012) claims that with 10 μJy rms, one can expect around 1 transient per degree. This is achievable by SKA Phase 1 mid frequency.

The SKA-International transient SWG is driven by key science of (i) FRB cosmology, (ii) Cosmic explosions and extreme astrophysics, (iii) black hole growth and feedback, (iv) Electromagnetic counterparts of gravitational waves transients. To be an optimal telescope for transient science, the international transient SWG has recommended mainly two changes to SKA Phase 1 design:

Commensal Transient Searches:

It is important to do near-real-time searching of all data for transient event. This will increase rate of events by at least one order of magnitude. Also the detection needs to be reported widely, globally and rapidly.

Rapid (robotic) Response to Triggers:

One may be able to detect very early-time radio emission (coherent or very prompt synchrotron) if SKA has Robotic response to external alerts, allowing very rapid follow-up of high-priority events.

For example, the Arcminute Micro-kelvin Imager Large Array (AMI-LA) is world's first robotic automated radio telescope. Its response time to Swift triggers are only 30 seconds. AMI has provided the first millijansky-level constraints on prolonged radio emission from GRBs within the first hour post-burst (Staley et al. 2013).

3 Transients research in India and role of SKA

In India active research is going on in transient astronomy, especially in the fields of supernovae (SNe), Supernova Remnants (SNRs), Gamma Ray Bursts (GRBs), Pulsars & related phenomenology, novae, X-ray binaries, tidal disruption events (TDEs), Galactic black hole candidates, and electromagnetic (EM) signatures in gravitational waves (GWs). Major observational facilities operated by National Centre for Radio Astrophysics (NCRA), Aryabhatta Research Institute of Observational Sciences (ARIES), Indian Institute of Astrophysics (IIA), Inter University Centre of Astronomy & Astrophysics (IUCAA) are widely used. Researchers also avail the wealth of archival data from high energy space missions like *RXTE*, *XMM Newton*, *SWIFT*, *Chandra* and *Fermi*. Groups are also working towards multimessenger astronomy mainly in the context of gravitational waves. As all members of this group have a significant international collaboration, we will have access to different observational facilities, both presently existing and to come in the future (e.g. Pandey et al. 2013).

Below we detail the research activities in various sub fields of transients in India.

3.1 Gamma Ray Bursts

Several groups have been working extensively on observations and theoretical modeling of GRB afterglows to pin down the details of GRB physics, e.g. Bhattacharya 2001, and Resmi & Bhattacharya 2008. Astrophysicists at TIFR and NCRA have been pursuing the physics of these extreme explosions with multi-frequency radio astronomy (both GMRT, EVLA and other large facilities, e.g. Chandra et al. 2012). Using optical telescopes by ARIES and IIA monitoring campaigns of several GRBs have been launched (Sagar & Misra 2005). The strategic location of Indian observatories in longitude have helped Indian groups to report earliest afterglow observations around the globe in a few cases and also to fill in many important data gaps. Indian Astronomers have collaborated internationally to assemble well sampled multi-wavelength afterglow lightcurves for several GRBs. Resmi & Zhang have studied the radio reverse shock emission for different shock dynamics and ambient medium models and have made predictions for the reverse shock emission to be seen in SKA and LOFAR bands. Kuntal Misra with her international collaborators is using Chandra, HST and EVLA to probe the late-time light curves which are required to put tight constraints on the existence and timing of jet breaks in the very energetic Fermi GRBs.

The combination of high sensitivity, high angular resolution, quick slewing time and broad band frequency range of SKA will be extremely crucial for GRB science through radio observations. Radio afterglows of GRBs can address crucial physics. The early time scintillations in radio bands can reveal the relativistic expansion of the jet (e.g. GRB 970508; Frail et al. 1997). The long lived radio emission has shown transition to non-relativistic regime, and help estimate accurate calorimetry of the burst (e.g. GRB970508, GRB030329). Early time reverse shock in GRB 130427 has constrained the afterglows models (Laskar et al. 2013). Radio is unobscured and can be used for GRB host galaxy observations, unaccessible to any other waveband. It can also find the missing population of orphan afterglows. SKA will facilitate to densely sample the lightcurve of all GRBs at different frequencies. Using over 300 examples of radio afterglow of GRBs, Chandra and Frail (2012) demonstrated that the detection rate of radio afterglows remain at 31 %, which has been disputed by Hancock et al. (2013) claiming that undetected afterglows are intrinsically dim. SKA will be very crucial in lifting this degeneracy. Chandra & Frail's synthetic light curves at centimetre and millimeter bands using a range of blast wave and microphysics parameters derived from multiwavelength afterglow modeling, can then be utilized to predict centimeter and millimeter flux behaviour of GRBs to be observed in new generation surveys like JVLA, ALMA, the various SKA precursor arrays and the SKA itself. Their synthetic light curves confirm that the radio afterglow flux density is only weakly dependent on redshift at $z \geq 2.5$ and so that SKA will be an important tool for discovery and followup of massive stellar explosions powered by central engines at cosmological distances.

Resolving ultra-relativistic outflows in GRBs is one field of interest. One would require SKA-VLBI observations of bright nearby GRBs. The full-Stokes SKA1-mid interferometer may also reveal polarization from GRBs. Longevity is the highest advantage of radio bands in studying GRB afterglows. A couple of very bright afterglows have been observed in time scale of several years by VLA and GMRT. SKA with its microJansky level sensitivity will be able to extend the current limits of afterglow longevity. 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 of the blastwave and changing shock microphysics. SKA era may also for the first time will be able to detect emission from counter-jet as the relativistic de-boosting disappears. Kuntal Misra plans to use SKA in her High energy burst program. Resmi plans to use SKA for studying GRB afterglows for investigating reverse shock emission, multi-band modeling and exclusive non-relativistic effects.

No orphan afterglows are ever reliably detected in spite of dedicated searches in optical and radio bands. Detection of this missing population is important in understanding the true rate of GRBs. It will also shed light to the structure and collimation of GRB jets. SKA will be able to do orphan afterglow searches more efficiently than before due to its high speed survey mode.

3.2 Core Collapse Supernovae

Supernovae (SNe) come into two basic types: 1. thermonuclear Supernovae (SNe-Ia), caused by the explosion of a massive white dwarf in a binary system. Their optical spectra are characterized by the absence of H lines and the presence of Si II absorption line; 2. Core-Collapse Supernovae, which mark the end of the life of massive stars. Astrophysicists at TIFR and NCRA have been pursuing the physics of supernovae for over a decade with multi-frequency radio astronomy (both GMRT, EVLA and other large facilities) as well as in the X-ray and optical bands (often simultaneously). Astronomers at IIA and ARIES are mainly involved in optical follow up of supernovae.

Radio emission from the interaction between explosion front shock and its surrounding circumstellar medium (CSM) or interstellar medium (ISM) provides an important probe to see their last evolution stage. After supernova explosion, the shock wave expels and heats the surrounding CSM and ISM, forming supernova remnants. Radio lightcurves are crucial to understand the history of the progenitor star. However, currently only $\sim 10\%$ of the discovered core-collapse SNe show radio emission. Only the radio-brightest SNe are detected, and systematic searches of radio emission from core-collapse supernovae (CCSNe) are still lacking, and only targeted searches of radio emission from just some of the optically discovered CCSNe in the local universe have been carried out. And this in spite of optical searches missing a significant fraction of CCSNe, largely due to dust obscuration. Therefore, radio supernova searches are much more promising for yielding the complete, unobscured star-formation rates in the local universe. As an obvious consequences of the increasing sensitivity of SKA, it will be possible to study a larger number of SNe (from current 2 radio detections/yr up to 50 detections/yr with SKA). We would also be able to follow-up each of them for a longer time. The commensal, wide-field, blind transient survey observations would result in an essentially complete census of all CCSNe in the local universe, as well as an accurate determination of the true volumetric CCSN rate, which is poorly known. While both SKA1-sur and SKA1-mid could are good strategies, the best option is likely to be that of using SKA1-sur at a frequency of 1.7 GHz, angular resolution 1", FoV 18 deg^2, good sensitivity 3.7 uJy/beam. SKA1-sur has survey speed 13 times of SKA1-mid. With an improved sensitivity level of 1 uJy, one can detect the brightest of radio SNe, such as the Type IIn SN 1988Z at the cosmologically interesting distance of z=1.

Despite their great cosmological importance, the exact nature of progenitors of SN-Ia remains unknown. While the canonical model is that the SNe itself is caused by thermonuclear explosion of a CO white dwarf (WD), initiated by accretion from a secondary, the nature of the secondary itself is still debatable. In the singly degenerate (SD) progenitor scenario, the H-and/or He-rich secondary could be a non-degenerate star which is either main sequence (MS), immediately post-MS, or even a late evolved red-giant, while in the double degenerate (DD) scenario it could be another WD in close contact binary, which merges in to the degenerate SNe progenitor, leading to the thermonuclear runaway reaction. Despite the very large number of optical observations of bright, nearby, SNe-Ia, which track the evolution of the SNe from shock outburst to nebular stage, the exact model has not yet been confirmed. Population synthesis studies of SD and DD models (Claeys et al. 2014; Ruiter et al. 2009) suggests that the DD channel is the most probable one, with multiple possible evolutionary sequences, leading to the formation of the close DD system. In any case, it is to be expected that mass loss would have occurred from the progenitor(s) prior to explosion, via stellar winds, Roche-Lobe overflow (RLOW), or in the common envelope (CE) phase, and a shock-CSM interaction should produce radio emission, with the low frequencies (e.g.) SKA bands reaching peak luminosity at a later time. This implies that the temporal, spectral and flux evolution of the radio emission would serve as a trace of the physical properties of SNe shock and CSM interaction.

To date, no SNe-Ia has been detected in the radio, though this could also be a selection effect, in that 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. E.g. for the nearby SN-Ia SN2014J (at 3.5 Mpc), only an upper limits on flux density in the eMERLIN (37.2 and 40.8 μJy at 1.55 and 6.17 GHz respectively), JVLA (12.0 and 24.0 μJy at 5.5 and 22 GHz respectively) and eEVN (28.5 μJy 1.66 GHz) are known, for epochs spanning upto 35 days post explosion (see Perez-Torres et al. 2014) – this lack of prompt emission appears to be consistent with the DD progenitor model. Thus, for nearby type-Ia SNe ($\simeq 2$ such events are detect 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. Based on radio observations, the current upper limit on the mass loss rate is

$3 \times 10^{-8} M_{\odot}$. SKA will hopefully detect radio emissions of Type Ia supernovae due to its much better sensitivity and resolution. However, even the lack of radio below $1 \times 10^{-10} M_{\odot}$ will rule out single degenerate model.

There is a supernovae rate problem for the core collapse supernovae. This is because the optically dim SNe are missing due to either being intrinsically faint or due to dust obscuration in the host galaxy. The SKA1-mid/survey will be able to detect many such dust obscured SNe, especially for those located in the innermost regions of host galaxies. Also the detection of intrinsically dim ones will also benefit from SKA1. The detection rate will provide unique information about the current star formation rate and the initial mass function.

Supernova explosion triggers shock wave which expels and heats the surrounding CSM and ISM, so forms supernova remnant (SNR). It is expected that more SNRs will be discovered by the SKA. This may decrease the great number discrepancy between the expected and observed. Several Supernova remnants have been confirmed to accelerate protons, main component of cosmic rays, to very high energy by their shocks. The cosmic ray origin will hopefully be solved by combining the low frequency (SKA) and very high frequency (Cherenkov Telescope Array: CTA) bands' observations.

The "bridging" relativistic supernovae like the recent SN 2012ap and SN 2009bb may be the missing link between explosions with lower symmetries which are powered by central engines versus those which are more symmetric supernova explosions powered by shocks that probe the circumstellar medium surrounding the exploding star. To understand the overall relationship between GRBs and supernovae many more examples of such "borderline" objects have to be discovered and studied, which is possible only with a wide-field, high sensitivity, broad-band and rapid cadence radio survey that SKA would execute. In this process untargetted synoptic surveys in other wavebands like the LSST will complement and synergise with SKA discoveries and followups.

3.3 Novae Outbursts

Novae form an important sub-class of transients in our Galaxy as well as in other galaxies. A nova outburst is triggered by runaway thermonuclear burning on the surface of an accreting white dwarf in an interacting binary system. With outburst energy in the range of 10^{38} to 10^{43} ergs, these events are amongst the energetic explosive ones. At an estimated rate of 30 novae per year (2002), these events are fairly frequent. Although the current observed rate is much lower than estimated, future deep surveys by facilities such as the LSST are expected to increase the number of observed events. 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. They also contribute to enriching the ISM with heavy isotopes of ^{13}C, ^{15}N, ^{22}Na and ^{26}Al. In addition, if the mass ejected during a nova outburst is less than that accreted since the last outburst, there is the possibility of the WD growing in mass, making (atleast some) of these systems interesting candidates for SNe Ia progenitors. However, despite their astrophysical significance as nearby laboratories, many aspects of these relatively common stellar explosions remain poorly understood. Although much of our current understanding of these systems has come from the optical observations, multi-waveband observations have augmented and enhanced our understanding. Radio observations play a key role in addressing some of the puzzling aspects of accretion, outburst and interaction with the environment.

Radio emission from novae typically lasts longer than the optical emission, on timescales of years, rather than months. Observations at different epochs yield information on different aspects of the nova outburst. While the very early phase observations provide information regarding the distance to the nova, as the nova evolves, the observations provide clues to the mass of the ejecta. The mass of ejecta is a fundamental prediction of nova models, and thereby provides a direct test of nova theory. 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, like in the case of GK Per (Sequist et al. 1989; Anupama & Kantharia 2005) and RS Oph (Hjellming 1986, Taylor et al. 1989, O'Brien 2006, Kantharia et al. 2007, Rupen et al. 2008, Sokoloski et al. 2008, Eyres et al. 2009). The *Fermi* detection of recent novae such as V407 Cyg 2010, V959 Mon 2012, V1324 Sco 2012 and V339 Del 2013 has revealed that shock interaction with the dense environment can also lead to GeV gamma ray emission.

The historical framework developed by R. Hjellming, E. Seaquist, A. R. Taylor, and others, have shown that radio observations provide unique insights into nova explosions. Since radio emission traces the thermal free-free emission, by extension it traces the bulk of the ejected mass. In addition, radio observations are not subject to the many complex opacity and line effects that optical observations both benefit and suffer from. Thus, being in addition to be relatively easier to interpret, radio observations can also probe how the ejecta profile and dynamic mass loss evolve with time. Radio observations of novae will thus illuminate the many multi-wavelength complexities observed in novae and test models of nova explosions.

G-nova team lead by G. C. Anupama propose 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 sensitivies 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. A sensitivity limit of 1 mJy can detect radio emission at < 1 GHz upto a distance of 10 kpc, if the non-thermal luminosity of the nova system is 10^{13} W Hz^{-1} (Kantharia 2012). An important motivation for studying the non-thermal radio emission from recurrent novae is to interrogate possible evolutionary connection to the lack of detectable radio emission from type Ia supernova systems.

3.4 Transient emission from Stellar mass compact objects

More than 2000 neutron stars have been detected in the last fifty years giving rise to a large number of distinct observational classes. The Rotating Radio Transients (RRATs), one of the new observational classes, are neutron stars detected originally through single-pulse emission (McLaughlin et al. 2006, Keane & McLaughlin 2011). It must be noted that because of the small number of pulses detected period measurements are not available for all of the known RRATs (only about 70 out of 100). Again for the same reason, measuring period derivatives for RRATs often requires much more observing time. normal pulsars due to their sporadic emission and only $\sim 25\%$ of the RRATs have measured period derivatives. The location of these RRATs in the 'magnetic field - spin period' diagram is therefore similar to that of the other non-recycled radio pulsars albeit with magnetic fields on somewhat higher side ($B \sim 10^{13}$ G).

A number of scenarios were proposed to explain this new observational class. Assuming them to be a completely separate population of neutron stars leads to the conclusion that in such a situation the inferred number of Galactic neutron stars would be totally at variance with the Galactic supernova rates (Keane et al. 2010). An obvious way out of this problem would be to assume that RRATs are simply members of the ordinary pulsar population and could perhaps be connected to them through some kind of evolutionary process. One such the hypotheses is that the RRATs are objects transitioning from normal pulsars to X-ray dim isolated neutron stars (XDINS). Or that they are somehow related to the magnetars. They have also been conjectured to be part of the normal pulsar intermittency spectrum - the case of extreme nulling, which have been shown not to hold much promise recently (Agarwal, Konar, Gajjar & Gupta, in prep).

Therefore it is imperative that in order to have a better understanding of this class of objects we have more data on them. With the SKA search and survey capability it would be possible to detect more of these objects. It would also be possible to undertake detailed studies of the single pulses and longer integration time would make it possible to have period derivative measurements (and hence an estimate of the dipolar magnetic field) of many more RRAT candidates. It would then be possible to answer the question whether RRATs are part of the ordinary pulsar population or actually belong to a separate class of neutron stars.

Accretion and ejection of matter is very common in cosmic objects of diverse scales, such as protostars, X-ray binaries and AGN. When the accreter is a compact object, e.g., a neutron star or a black hole, probing accretion and ejection can provide a unique tool to test a law of gravitation, such as general theory of relativity, in strong gravity regime, and to understand the magneto-fluid dynamics in this regime. There can be several components of the accretion structure, for example, accretion disk, corona, etc. The ejection of matter can happen through jet and wind. All these components are connected to each other, and such connections provide an important clue to the accretion-ejection mechanism in the strong gravity region. For transient X-ray binaries, the interdependencies among and contributions from various components evolve in a time scale of hours to months, and provides a unique opportunity to address the above mentioned scientific problems. This is a major motivation for Sudip Bhattacharyya to study the evolution of transient X-ray binaries.

Among the components of a transient X-ray binary system, jets are usually imaged in radio, although they can also emit in other wavelengths. A jet is particularly useful, because, if in a black hole system it is powered by the black hole spin, then that will show that energy can be extracted from a spinning black hole. It is known that the strength and nature of a jet evolves with the intensity and state evolution of transient X-ray binaries. A study of a correlation of such a jet with various timing and spectral features in X-rays, IR and other wavelengths is essential to probe the accretion-ejection mechanism and the strong gravity regime. So it will be extremely important to detect and characterize the jets in radio in short time scales. SKA will be able to do this even when jets are relatively faint in radio, and hence will make significant progress in this field. Sudip Bhattacharyya proposes to observe transient X-ray binaries throughout their outbursts with SKA.

Manjari Bagchi works on different aspects of neutron star (NS) physics, including the Equation of State, observable properties of NSs, testing theories of gravity with binary NS, etc. Among different types of NSs, she is particularly interested in radio pulsars and have studied orbital properties and luminosity distributions of radio pulsars in and out Galactic globular clusters and in the disk. She also works on population synthesis study of neutron star neutron star binaries. Increased number of binary pulsars discovered by SKA will help to check/improve such theories of evolution of binary NS, as well as the population. She wishes to explore higher order post-Newtonian effects in such systems. She is also interested in X-ray observations of accreting neutron stars (which are believed to be progenitors of recycled radio pulsars having spin-periods in the order of milliseconds) and gamma-ray emitting neutron stars. Neutron star black hole (NSBH) binaries will be the best tools to test such theories. It is expected that such systems will be discovered by SKA. In particular, the spin-orbit coupling effect in the cases of neutron star neutron star binaries might help constraining the dense matter Equation of State using binary pulsar data. SKA might lead to the discovery of new neutron star neutron star binaries having much larger spin-orbit coupling, eventually enabling us this goal.

3.5 Tidal Disruption events

Ultra-luminous cosmic explosions, such as tidal disruption events (TDEs), are the sites of the most extreme astrophysics in the universe, allowing us to probe pressures, energy and matter densities, speeds and gravitational curvature far in excess of anything we will ever achieve in a laboratory. They represent the most extreme environments since the Big Bang. Tidal disruption of stars by supermassive blackholes have long been studied both theoretically and observationally. Typically, thermal 'flares' in optical to X-ray ranges were predicted and observed. However, recently a peculiar long lasting high energy transient (Swift 1644+57) was observed and was interpreted as a tidal disruption event (TDE). Unlike other tidal disruption events, this had a bright radio counterpart. An ultra-relativistic jetted outflow is believed to be the reason for its unique properties. The Swift 1644+57 like jetted TDEs (at redshift z = 0.35) also launch relativistic jets possibly in a similar manner to the radio jets in AGNs which allow probes of the inner environments surrounding the supermassive black hole. Research on these types of transients being pursued by Indian astronomers at TIFR/NCRA using the multiwaveband approach (whose backbone is radio astronomy) is revealing the nature of the progenitors and the environment that they exploding in.

Bright radio flaring occurring during transient Eddington-level accretion onto supermassive black holes. As TDEs stay bright over timescales of months, these are potential candidates to study Super-Eddington accretion, jet formation and disk-jet connection in great detail. Key is to understand transient accretion onto supermassive black holes kinetic feedback over to cosmological time Radio flares due to ultra-relativistic outflows arising from tidal disruption events are a potential probes of quiescent SMBHs in the centers of galaxies. The fast survey mode of SKA is likely identify 100s to 1000s TDEs per year. This can greatly enhance our understanding of SMBH mass function. Kuntal Misra and L Resmi are interested in using SKA for probing this unexplored regime.

3.6 Fast Transients

Fast timescale (¡5s) transients probe high brightness temperature emission and probe extreme states of matter and throw light on physics of strong gravitational fields. Extragalactic fast transients probe the ionized IGM and are cosmic rulers. Avinash Deshpande is involved in a project in which more than 1000 hours of observations covering the entire Arecibo sky have been made using the ALFA in Meridian nodding mode, as a part of the GALFACTS continuum Full Stokes (polarization) imaging project. ALFA is a L-band, seven pixel, system with 300-MHz BW. One of the streams resulting from these observations was designed to enable data for transient search, with spectral-resolution of about 1 MHz, and time-resolution of 1 ms. In addition, Yogesh Maan and Avinash Deshpande have a sky survey at 35 MHz from Gauribidanur, covering the GBD sky, providing data on 3000 fields observed with 20 minutes each, with raw voltages recorded across a 1 MHz bandwidth. These data were used partly for searches of radio counterparts of the FERMI-LAT detections.

Fast radio bursts (FRB) are a recently discovered class of radio transients which are of very short duration ($\sim$ millisecond), show characteristics of propagation through cold, diffuse plasma, and likely originate at cosmological distances. However, the understanding of the physical origin of FRBs remains as an open challenge. There is a significant interest among Indian researchers to work on FRBs, both observationally and theoretically. Manjari Bagchi is interested in theoretical understanding of FRBs, as well in searching for new FRBs in the pulsar surveys she is involved at present and will be in the future. Poonam Chandra is following the Parkes FRB triggers with GMRT for the afterglow emission. Moreover, there is an ongoing project to develop a transient detection system at GMRT (Bhat et al. 2013), which might be very successful to detect FRBs. Yashwant Gupta and Jayaram N. Chengalur are involved in this project along with many other Indian and foreign colleagues.

FRBs are indeed the biggest discovery of the decade. FRBs seem common (10^4 sky^{-1} day^{-1}) and quite bright (detectable to z¿1 even with Parkes!) The main steps in FRB detections are: Detection, verification and localisation & Followup. The wide field of view of SKA is quite useful in this, however, wide field of view commensality is essential for a 20 sq. deg. FoV at 10^4 events/sky/day results in ~ 5 events per day.

The detection and localisation of thousands of coherent bursts 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 determine the dark energy equation of state at redshifts ≥ 2. The SKA can achieve 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 (1ms) signals. High precision cosmology with fast radio bursts is a very useful field. SKA1-LOW and SKA1-Survey will be the useful telescope for this.

Searches for fast radio transients in the lower frequency part of the spectrum (a few tens of MHz to a few hundreds of MHz) could also be revealing. At frequencies ≤ 100 MHz, relatively nearby "Lorimer Bursts" (Lorimer et al. 2007) and coherent emission bursts from neutron stars (e.g., giant pulses and burst emission from radio pulsars, sporadic individual pulses from RRATs, etc.) would give rise to sub-second transient signals. Yogesh Maan is carrying out a search for fast transients towards several selected directions at a very low frequency of 34 MHz, using the Gauribidanur radio telescope. So far, this search has resulted into potential discovery of a few radio bursts at very low dispersion measures, and that of a nearby pulsar. A sensitive survey for nearby pulsars is also being conducted towards these selected directions. With a wide field of veiw, high sensitivity and good sky-position localization, SKA-low holds great potential to discover fast transients, pulsars and possibly new class of objects at these relatively less explored low radio frequencies. In addition to the searches for transients and pulsars at several low frequency bands, Yogesh Maan has also been pursuing research related with several puzzling details of the radio emission from known pulsars, e.g., sub-pulse drifting, nulling, mode-switching etc. SKA-low and SKA-mid will certainty help in finding out more observational clues to probe the physical mechanisms of the pulsar radio emission.

Recently Avinash Deshpande has proposed a broadband Indian SWAN Sky Watch Array Network (SWAN). Indian-SWAN is a proposed competitive coordinated network with nominally 1000 sq. m array area at each location and operation spanning a decade in frequency; 50–500 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 study. Manjari Bagchi is involved in two pulsar surveys, one is a drift-scan survey using the Arecibo radio telescope, and the other one is a small-scale survey using GMRT. As she has already searched for radio transients like, Rotating Radio Transients (RRATs), Fast Radio Bursts (FRB) and Perytons in the archival Parkes Multibeam Pulsar Survey, she intends to search for such objects in above-mentioned surveys too.

3.7 Multi-messenger astronomy

Electromagnetic counterparts of gravitational waves are another important transients field of research with SKA. Discovery of the electromagnetic counterparts of gravitational wave sources would be a major breakthrough and vital in understanding their origin (e.g. merging neutron stars, black hole merger rates), especially in the case that the gravitational wave and electromagnetic signal provided two completely independent distance measurements on cosmological scales. Manjari Bagchi is a member of IndIGO (Indian Initiative in Gravitational-wave Observations). She also collaborate with the people involved in the International Pulsar Timing Array (IPTA) and hoping to increase the collaborative activities. K G Arun is interested in modelling of compact binaries and investigating the study of various astrophysical phenomena associated with it. One of his research interests is to study the astrophysical implications of observing a short Gamma Ray Burst (SGRB) in association with a gravitational wave (GW) signal from compact binary mergers (NS-NS or NS-BH). He was involved in a parameter estimation study of GW signals and studying the how it can impact and complement SGRB afterglow modelling.

On a time scale of years to decades, gravitational wave (GW) astronomy is most likely bound to become a reality. Ultra-low frequency (10^{-9} – 10^{-8} Hz) GWs are detectable through long-term, high precision pulsar timing observations of the most stable pulsars. Observatories worldwide are currently carrying out observing programs to detect such waves and their data sets are being shared as part of the International Pulsar Timing Array project. No GW signal has yet been detected, but stringent constraints are already being placed on models for galaxy evolution. The SKA will be the ideal telescope to bring this research to fruition. If operated jointly with the then operational GW interferometers, SKA may be able to use the information about the location of the compact binary merger inferred from GW observations in carrying out such searches. This may significantly enhance the efficiency of such searches. Hence radio follow ups of SGRBs associated with GWs or GW triggered searches for radio counterparts associated with compact binary mergers are extremely important from an astrophysical point of view which SKA will be able to carry out very effectively. K G Arun would like to study in detail the possible implications of such joint observations.

Nayantara Gupta is working in theoretical modeling of high energy particle emission from astrophysical sources and investigating on the possible origins of the IceCube detected high energy neutrino events. So far no statistically significant correlation of IceCube events has been found with the known steady astrophysical sources so far. Neutrino emission is also possible from flares and transients. Some of the radio transients could be sources of high energy gamma rays and neutrinos. Nayantara Gupta is interested in studying neutrino signatures arising from the transient events. The dynamic sky to be observed by SKA could provide new sources of these high energy particles.

4 Conclusions

With the high sensitivity and wide-field coverage of the SKA, very large samples of such explosive transients are expected to be discovered. A major fraction of these will be TDE events followed by type II SNe and orphan afterglows of GRBs and relativistic supernovae. Even at the ASKAP (precursor) stage, VAST-Wide surveys conducted at 1.2 GHz band for about 10,000 square degrees in about every fortnight will typically be expected to yield some 32 type II SNe, 82 Swift 1644+57 TDE events, 8 orphan afterglows etc. (Frail et al 2012). The large number of such newly discovered sources will be a rich harvest among which there will be quite a few that will have characteristics (such as radio brightness, counterparts at other wavebands or other physical characteristics like outflow properties) that will make it possible to follow them up intensively with high cadence. Not only will these new discoveries trace out well-populated areas of phase space of explosions, but quite likely, they will provide hitherto unknown linkages that will clarify or strengthen suspected unity among diversity. They will clarify the underlying physical processes with a far greater precision. Radio wavelengths are particularly well suited for uncovering such phenomena in synoptic surveys, since observations at radio wavelengths may suffer less obscuration than in other bands (e.g. optical/IR or X-rays) due to dust and other absorption. At the same time a multiwaveband approach is a "force-multiplier", since source identification becomes more secure and multiwaveband information often provides critical source classification rapidly than possible with only radio band data.

Our strategy will be to develop tools with machine learning capabilities to automatically and rapidly classify the transient events expected in the SKA era and follow up a few of these intensively and with multiwaveband coverage through other large facilities that India will likely have access to. These exceptional few objects have the potentials for discovery of major underlying physical processes and trends. For example the abundance of relativistic supernovae without GRB counterparts, and luminous TDE events will have implications among other things on the sources of Ultra High Energy Cosmic Rays within the Greisen (GZK) cutoff distance from the Earth (Chakraborti et al 2011).

The SKA will be a premier instrument for transient science. This strength of the science case will continue to increase as more and more class of transients are discovered with current surveys. 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.

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Neutron Star Physics in the SKA Era: An Indian Perspective

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1 Introduction

Since the first detection of a neutron star as a radio pulsar (Hewish et al. 1968), we now have some $\sim$ 2500 objects detected with diverse characteristic properties across almost the entire electromagnetic spectrum (Manchester et al. 2005). A consequence of this is the emergence of a large number of distinct observational classes. Interestingly, the processes responsible for the generation of the observed emitted energy are basically of three types. This leads to a simple classification of the neutron stars according to the nature of energy generation in them (Konar 2013). Primarily, we have - the rotation powered pulsars (RPP) powered by the loss of rotational energy due to magnetic braking; and the accretion powered pulsars (APP) where material accretion from a companion gives rise to energetic radiation. Then there is the new class of internal energy powered neutron stars (IENS) (for want of a better name) where the emission is suspected to come from their internal reservoir of energy (be it that of a very strong magnetic field or the residual heat of a young neutron star) (Kaspi 2010).

Over the years, the study of this huge variety of neutron stars has mainly been focused into three primary areas - i) to understand the evolutionary (or otherwise) connection between the distinct observational classes, ii) to understand the physical processes relevant in and around a neutron star and iii) to use the neutron stars as tools to understand certain aspects of fundamental physics.

All of these areas are expected to receive a tremendous boost with the advent of new generation instruments. In particular, because neutron star astronomy depends greatly on radio observations, the SKA era would be of paramount significance. Potential applications include pulsar search and survey, pulsar magnetospheric studies, characterizing gravitational wave candidates,

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detection of transient objects (like RRATs) and so on. These will provide new insights and results in topics of fundamental importance. The combination of the high spectral, time and spatial resolution and the unprecedented sensitivity of the SKA will radically advance our understanding of basic physical processes operative in the vast population of neutron stars and provide a solid foundation for the future advancement of the field. The extent of such impact has recently been discussed in great detail in the international neutron star community (Tauris et al. 2015; Watts et al. 2015; Keane et al. 2015; Shao et al. 2015; Hessels et al. 2015; Karastergiou et al. 2015; Eatough et al. 2015; Gelfand et al. 2015; Antoniadis et al. 2015). Therefore, in this document we only record the areas of particular interest to the Indian scientists working in different areas of neutron star physics.

2 Neutron Stars : The Population

2.1 Evolutionary Pathways

Classifying the neutron stars according to their energy generation mechanisms, we can now generate the following taxonomy.

Rotation Powered Pulsars (RPP) : - As of now, there are about three types that fall into these category. A) These are mainly the classical radio pulsars (**PSR** - $P \sim 1$ s, $B \sim 10^{11} - 10^{13.5}$ G), powered by the loss of rotational energy due to magnetic braking. B) Among the current sample of 2000+ radio pulsars known primarily in our Galaxy, millisecond radio pulsars (**MSRP** - $P \lesssim 20$ ms, $B \lesssim 10^{10}$ G) now number almost 200 (Lorimer 2009). This famous (and initially the only) sub-class of RPPs, have different evolutionary histories, involving long-lived binary systems and a 'recycling' accretion episode reducing both the spin-period and the magnetic field (Tauris 2011). C) The mildly recycled pulsars (**MRP**), defined as objects with $P \sim 20 - 100$ ms and $B_p < 10^{11}$ G. The rotating radio transients (**RRAT**) are also likely to be a sub-class of RPPs; suspected to be extreme cases of nulling/intermittent pulsars.

Accretion Powered Pulsars (APP) : - Depending on the mass of the donor star these are classified as High-Mass X-ray Binaries (HMXB) or Low-Mass X-Ray Binaries (LMXB). A) Neutron stars in HMXBs typically have $B_p \sim 10^{12}$ G and O or B type companions and mostly show up as an X-ray pulsars (**XRP**) (Caballero & Wilms 2012). B) LMXBs, on the other hand, harbour neutron stars with magnetic fields significantly weakened ($B \lesssim 10^{11}$ G) through an extended phase of accretion. Physical process taking place in such accreting systems are manifested as - thermonuclear X-ray bursts; accretion-powered millisecond-period pulsations; kilohertz quasi-periodic oscillations; broad relativistic iron lines; and quiescent emissions (Bhattacharyya 2010). These have given rise to two exciting observational classes in recent times - the accreting millisecond X-ray pulsars (**AMXP**) and the accreting millisecond X-ray bursters (**AMXB**).

Internal Energy Powered Neutron Stars : - The connecting link between these classes is the fact that the mechanism of energy generation is not obvious for any of them. For most part it is suspected that the decay of a strong magnetic field or residual cooling might be responsible for the observed emission. A) **Magnetars** are thought to be young, isolated neutron stars and they shine because of the decay of their super-strong magnetic fields and are actually related to soft gamma ray repeaters (**SGR**) and anomalous X-ray pulsars (**AXP**). It is believed that the main energy source of these objects is the decay of super-strong magnetic fields (magnetar model) (Thompson & Duncan 1996). B) The handful of X-ray bright compact central objects

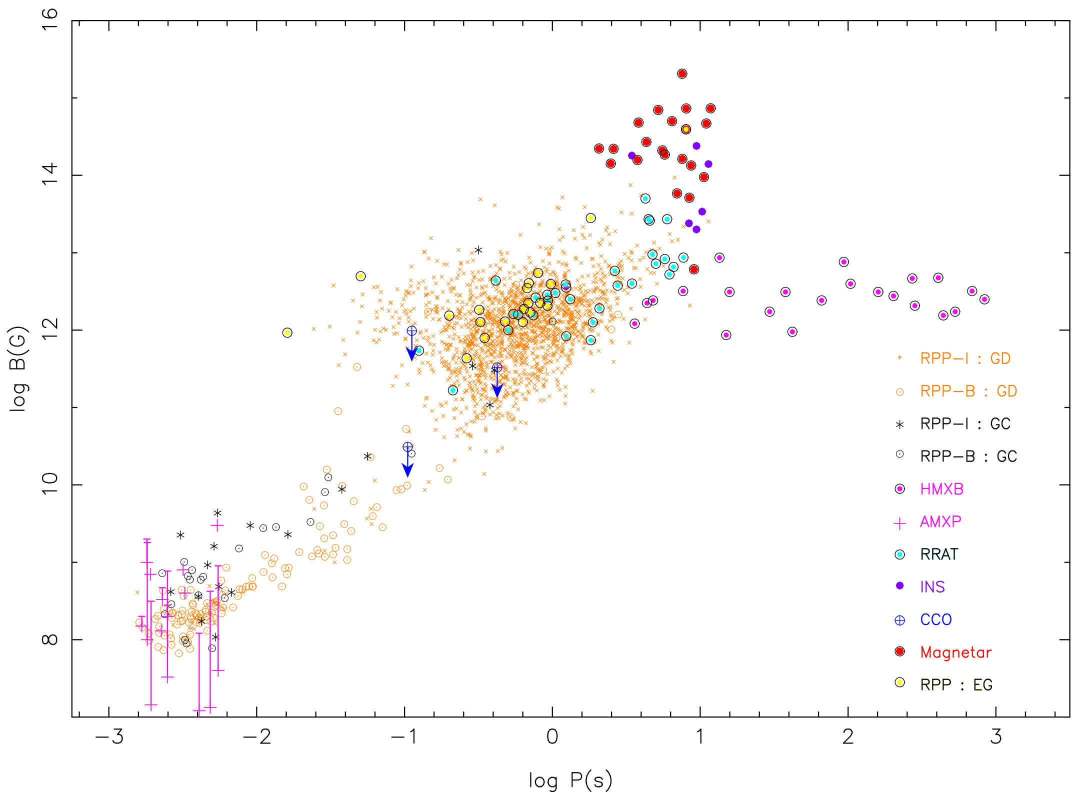

Figure 1: Different observational classes of neutron stars (with some measurement/estimate of the magnetic fields) in the $P-B$ plane.
Data : RPP - ATNF pulsar catalog, RRAT - `http://astro.phys.wvu.edu/rratalog/`, Magnetar - `http://www.physics.mcgill.ca/ pulsar/magnetar/main.html`, AMXP - Patruno & Watts (2012), Mukherjee et al. (2015); HMXB - Caballero & Wilms (2012), INS - Haberl (2007), Kaplan & van Kerkwicjk (2009); CCO - Halpern & Gotthelf (2010), Ho (2013);
Legends : I/B - isolated/binary, GC - globular cluster, GD - galactic disc, EG - extragalactic objects

(**CCO**) are characterised by absence both of associated nebulae and of counterparts at other wavelengths and exceptionally low magnetic fields ($B \sim 10^{10}$ G). It has been suggested that a regime of hypercritical accretion immediately after the birth of the neutron star could bury the original field to deeper regions of the crust (Viganò & Pons 2012). C) The seven isolated neutron stars (**INS**), popularly known as *Magnificent Seven*, are optically faint, have blackbody-like X-ray spectra ($T \sim 10^6$ K), relatively nearby and have long spin-periods ($P \sim -10$ s). They are probably like ordinary pulsars but a combination of strong magnetic field and spatial proximity make them visible in X-rays.

One of the prime challenges of neutron star research has always been to find a unifying theme to explain the menagerie presented by the disparate observational classes (shown in Fig.1]) of the neutron stars. The magnetic field, ranging from 10^8 G in MSRPs 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 neutrons star 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 through decades of investigation by a number of researchers. For example, the connection between the ordinary radio pulsars with their millisecond cousins via binary processing is now an established evolutionary pathway (Bhattacharya 2002; Konar 2013; Konar, Mukherjee, & Bhattacharya 2015). On the other hand, to understand the connection between different types of isolated neutron stars a detailed theory of magneto-thermal evolution is being developed only in the last few years (see Pons, Miralles, & Geppert (2009); Kaspi (2010); and Vigano (2013) for details of these model and other references). Therefore, it appears that a scheme of grand unification, encompassing all the varieties, has started to emerge now. And it is expected that in the SKA era important gaps in this unification scheme could be filled.

2.2 Evolution of HMXBs

While the double neutron star binaries and the yet to be discovered (NS-BH) binaries are the most promising candidates for the gravitational wave detectors, formation rates of such systems depend crucially on the formation, co-evolution, and survival rates of the massive binary stellar systems. One important phase of such binaries, in which their evolution can be measured with high accuracy is the HMXB phase in which one component has evolved to a compact star, most often a high magnetic field neutron star. The accreting neutron star in such a system is an X-ray pulsar that enables accurate measurement of the orbital parameters and its evolution. In almost all of the accreting X-ray pulsars with super-giant companion star, the orbital evolution time scale is found to be short, less than a million year suggesting a tidal force driven orbital evolution (Paul et al. 2011). The evolution of such systems, leading to formation of NS-NS or NS-BH binaries in some of them therefore must account for the measured orbital decay rates of such systems. The orbital decay may lead to more compact configuration which will increase the survival rate during the second supernova explosion and the decay may also lead to complete spiral-in which will lead to a single remnant. The orbital evolution of a handful of such systems have been done so far and more measurements of orbital decay of HMXBs are expected with ASTROSAT and future X-ray timing instruments. This would have impact on the rate of NS-NS and NS-BH binary searches with SKA and eventually have an impact on event rate of gravitational wave detectors.

2.3 Transition Pulsars

MSRPs are thought to be spun up by a billion-year-long phase of angular momentum transfer in LMXBs (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982). While this hypothesis is widely accepted, till recently, a direct connection between MSRPs and LMXBs was not established, because radio pulsations were not observed from an LMXB. This is very important to understand the binary evolution and accretion processes, because the extent of spinning up depends on (1) the evolution of accretion rate and structure due to the evolution of the binary properties, (2) whether accretion primarily happens via a geometrically thin accretion disk and hence transfers a large amount of angular momentum, (3) what fraction of the accreted matter leaves the system via jet and wind, (4) whether accretion happens continuously or intermittently, and so on. Observation of radio pulsation from an X-ray binary also gives us a unique opportunity to study how pulsar radiation and pulsar wind nebula affect the accretion process. Recently, three sources (PSR J1023+0038, PSR J1227-4853, PSR J1824-2452I) have shown transitions between the radio pulsar phase and the LMXB phase (Archibald et al. 2009; Roy et al. 2014; Papitto et al. 2013). Each of the three systems is a Redbacks system, that is a binary stellar system with an ms pulsar and a main-sequence star rotating around each other. These discoveries have confirmed that such sources can change between radio pulsar state and LMXB state back and forth. Moreover, various low-intensity X-ray states have recently been reported for these sources (Linares 2014). So, as mentioned earlier, the systems showing both radio pulsar and LMXB phases can be very useful to probe binary evolution, accretion-ejection mechanism, and so on. In order to achieve this, it is essential to discover as many such systems as possible, and study them in both radio and X-rays in various intensity states. So far, roughly 18 red-back systems are known. SKA will increase this number by at least a factor of a few (Keane et al. 2015). Moreover, the two phases may be discovered even from non-redback sources. The radio pulsation phase of this increased population should be observed and monitored with SKA. When the radio pulsation disappears, or when the source X-ray intensity increases as detected with X-ray monitors, X-ray pointed observations should be done. This way the above mentioned scientific problems can be addressed very effectively by observations with SKA and proposed X-ray observatories such as Astrosat and Athena.

2.4 Population Synthesis Studies

Population synthesis study means the effort to understand the cumulative properties of neutron stars in different 'classes' and to reveal the underlying physics behind such observed properties. The simplified method of population synthesis study is the so called 'snapshot' method where people study the observed properties of one or more 'classes' or 'sub-classes' (Hui, Cheng, & Taam 2010; Konar 2010; Papitto et al. 2014). This method is not always sufficient to reveal the true characteristics of a 'class' of neutron stars, mainly because of our limitations in observing neutron stars. So detailed 'full dynamical' method becomes unavoidable (Bhattacharya et al. 1992; Faucher-Giguère & Kaspi 2006; Story, Gonthier, & Harding 2007; Ridley & Lorimer 2010). In this method, one first chooses a set of initial parameters for the objects belonging to the 'class' or 'classes' under investigation (Monte-Carlo simulations), then model the evolution of the objects with chosen parameters, as well as their observability, i.e. the probability of detection. Finally one justifies the choice of initial parameters, evolutionary models, etc., by comparing the 'observable' properties of the synthetic set of objects with the observed properties of such objects. This method sometime reveals interesting properties of the objects under investigation, e.g., the study by Bhattacharya et al. (1992) first established the fact that the magnetic field of isolated rotation powered radio pulsars does not decay. Sometimes, methods intermediate between the 'snapshot' approach and the 'full dynamical' approach have been used (Lorimer et al. 1993; Hansen & Phinney 1997; Bagchi, Lorimer, & Chennamangalam 2011; Gullón et al. 2014). Note that, because of the complexity of the 'full dynamical' approach and uncertainties in initial conditions, this method is more popular to study isolated radio pulsars with the initial point of the evolution started at the birth of the neutron stars. In principle, one can perform the study starting from the zero age main sequence phase of the progenitor of the neutron star, as theory of evolution of massive stars is well known. Similarly, there are many studies on evolution and formation of neutron stars in binaries (Bhattacharya & van den Heuvel 1991; Verbunt 1993; Portegies Zwart & Yungelson 1998; Dewi, Podsiadlowski, & Sena 2006; Belczynski et al. 2008; Kiel et al. 2008; Tauris et al. 2013), where the evolution and detectability of binary radio pulsars had not been studied. Thus population synthesis remains as an open avenue, which might shed more light to the physics of different sub-classes of rotation powered pulsars (like 'Rotating Radio Transients') which are not yet so well understood. Population synthesis will be useful for other areas of research, including gravitational wave astronomy, short GRB etc. Moreover, there is enough scope to employ population synthesis methods to other 'classes' of neutron stars, e.g., accretion powered X-ray pulsars.

It is expected that the SKA will lead to discoveries of more rotational powered radio pulsars (Smits et al. 2009; Smits et al. 2011). This larger data set will enable us to test existing and future population synthesis studies better. Also, due to its higher sensitivity and execution of motivated pulsar surveys, SKA might discover expected sub-classes of rotational powered pulsars including pulsars with stellar mass black holes as companions, pulsars very close to the Galactic centre, etc., and probably even some unexpected/unknown sub-classes. Presently, GMRT is being widely used for pulsar surveys and will be used for such purposes in the near future. Successes and failures of pulsar surveys with GMRT will help to devise efficient pulsar surveys using SKA.

2.5 Statistical Studies

The SKA is expected to enrich the neutron star catalogs by at least an order of magnitude over their current state. This includes the discovery of new objects, related phenomena such as nulling, glitching, etc., as well as precision measurements of intrinsic properties such as spin period and magnetic field. This will present a unique opportunity to seek answers to interesting questions about these exotic objects in the universe.

An empirical research direction in this context is the taxonomy of neutron stars and also magnetospheric phenomena such as pulsar nulling and glitching. This direction is broadly defined by questions such as

- What different categories of neutron stars are suggested by the data?
- What do the data say about the possibility of more than one mechanisms for pulsar glitches?
- Considering the expected data volumes, can pulsars be categorized agnostically in the context of emission phenomena such as nulling, mode changing, etc., and how would these categories compare with existing classifications? For example, can nulling pulsars be categorized using pulse energy distributions?

- What do the data speak about the probable evolutionary pathways for neutron stars?

Guided by astrophysical insight, such empirical, data-driven research can benefit immensely from the use of advanced statistical methods for data modeling, clustering/classification, density estimation, regression, and statistical/machine learning in general (Hastie, Tibshirani, & Friedman 2009; Wasserman 2004; Wasserman 2006). In the context of existing or empirical data-driven classification/clustering studies, two types of objects deserve special attention; namely, the most "typical" element/s in a class, and potential outliers. These can be identified using methods based on, e.g., *data depth* (Liu, Parelius, & Singh 1999) or *outlyingness* (Brys, Hubert, & Rousseeuw 2005). A separate investigation of such typical or atypical elements of a class may lead to rich insights into the physics of NS.

Indeed, recent investigations have led to promising methodological exploration and development (including adaptation and apt use of existing statistical methods) for addressing questions related to

- pulsar nulling, using Gaussian mixtures to model arbitrary-shaped single-pulse energy distributions (Arjunwadkar, Rajwade, & Gupta 2015; Rajwade et al. 2015);
- pulsar micro-structure, using non-parametric regression to model arbitrary single-pulse shapes (Mitra, Arjunwadkar, & Rankin 2015);
- multiple populations in glitch data, using hypothesis tests for (uni)modality, Gaussian mixtures to model glitch energy and momentum distributions (Konar & Arjunwadkar 2014; Konar & Arjunwadkar 2015); and
- categorization of NS using their intrinsic properties, using clustering based on spin period and magnetic field as features (Arjunwadkar, Kashikar, & Konar 2015).

The methodological viewpoint inherent in all these above works is that the nature of data and the questions being asked should dictate the method, and not *vice versa*.

To understand their limits and suitability, methodologies – old or new – need to be explored and tested thoroughly using available data and observational instruments, while keeping in mind that eventually the data volumes may be much larger. Involvement of researchers (from allied fields such as statistics and computer/computational science) with a multidisciplinary outlook and openness to step outside of their traditional comfort zones should certainly help bring in fresh methodological perspectives. This will go a long way in utilizing the full potential of the SKA for answering fundamental questions about NS.

3 Neutron Stars : In & Around

3.1 Probing the Interior

Shortly after the discovery of pulsars, the study of dense matter in the core of neutron stars had gained momentum (Glendenning 1996). The rapid accumulation of data on compact stars in recent years may shed light on the gross properties of cold dense matter far off normal nuclear matter density. Neutron star matter encompasses a wide range densities, from the density of iron nucleus at the surface of the star to several times normal nuclear matter density in the core. Since the chemical potentials of nucleons and leptons increase rapidly with density in the interior of neutron stars, several novel phases with large strangeness fraction such as, hyperon matter, Bose-Einstein condensates of strange mesons and quark matter may appear there. It is to be noted that strange matter typically makes the equation of state (EoS) softer resulting in a smaller maximum mass neutron star than that of the nuclear EoS (Glendenning 1996).

Observed masses and radii of neutrons are direct probes of compositions and EoS in neutron star interior. The theoretical mass-radius relationship of compact stars could be directly compared with measured masses and radii from various observations. Consequently, the composition and equation of state (EoS) of dense matter in neutron stars might be constrained. Neutron star masses have been estimated to very high degree of accuracy. This has been possible because post-Keplerian parameters such as time derivative of orbital period, advance of periastron, Shapiro delay, Einstein time delay were measured in several pulsars. Currently the accurately measured highest neutron star mass is 2.01±0.04 $M_\odot$ (Antoniadis et al. 2013). This puts a strong constraint on the EoS of neutron star matter. Those EoS which can not satisfy the 2 $M_\odot$ constraint, are ruled out (Banik, Hempel, & Bandyopadhyay 2014).

Unlike masses, radii of neutron stars have not been accurately measured yet. After the discovery of highly relativistic binary systems such as the double pulsar system PSR J00737-3039 for which masses of both pulsars are known accurately, it was argued that a precise measurement of moment of inertia (I) of one pulsar might overcome the uncertainties in the determination of radius (R) because dimensionally $I \propto MR^2$ (Lattimer & Schutz 2005). In relativistic binary systems, higher order post Newtonian (PN) effects could be measured. Furthermore, the relativistic spin-orbit (SO) coupling may manifest in an extra advancement of periastron above the PN contributions such that the total advance of periastron is $\dot{\omega} = \dot{\omega}_{1PN} + \dot{\omega}_{2PN} + \dot{\omega}_{SO}$ (Damour & Schafer 1988). The SO contribution has a small effect and could be measured when it is comparable to the 2PN contribution. The measurement of the SO effect leads to the determination of moment of inertia of a pulsar in the double pulsar system (Watts et al. 2015; Shao et al. 2015). With the present day timing accuracy for the pulsar A of PSR J0737-3039, the determination of moment of inertia at 10 percent level would take about 20 years.

This situation would change with the advent of the SKA. Substantial advancement in the timing precision is expected to come from the SKA. The high precision timing technique in the SKA would determine the moment of inertia of a pulsar earlier than that in the present day scenario. The accurate determination of masses and moments of inertia of pulsars in relativistic binary systems with the SKA leads to simultaneous knowledge about masses, radii and spin frequencies of pulsars which would be used to confront different theoretical models and constrain the EoS and compositions in neutron star interior or even yield the EoS in a model independent way inverting the Tolman-Oppenheimer-Volkoff equation (Lindblom 1992). The EoS and compositions of dense matter extracted from neutron star observations are also important for the construction of EoS tables for core collapse supernova (CCSN) simulations, neutron star mergers and understanding the appearance of strange matter in the early post bounce phase of a CCSN (Banik, Hempel, & Bandyopadhyay 2014).

The spin off from the measurement of moment of inertia in the SKA era will be many folds. It was already predicted that the plot of moment of inertia versus rotational velocity (Ω) might reveal some interesting features of pulsars. It was shown that after the initial spin down of a pulsar along a supra-massive sequence, there was a spin up followed by another spin down in the I vs. Ω plane (Weber 1999; Zdunik et al. 2004; Banik et al. 2004). This is known as the back bending (S-shaped curve in the plot) phenomenon. This phenomenon was attributed to the strong first order phase transition from nuclear matter to some exotic (hyperon, kaon condensed or quark) matter. The SKA might provide an opportunity to investigate the back bending phenomenon and the existence of exotic matter in pulsars.

Another interesting possibility is the presence of super-fluidity in neutron star matter. Generally it is inferred that pulsar glitches are the manifestation of super-fluid neutron matter in neutron stars (Andersson et al. 2012). Recently, it has been argued whether the moment of inertia of the superfluid reservoir in the inner crust is sufficient to explain the latest observational data of pulsar glitches or not (Andersson et al. 2012; Chamel 2013). When the entrainment effect which couples the neutron superfluid with the crust, is taken into account, a larger angular momentum reservoir is needed for observed glitches (Andersson et al. 2012). Consequently, the required superfluid moment of inertia exceeds that of the superfluid crust. This indicates that some part of the superfluid core would contribute to pulsar glitches. It would be worth investigating the super-fluidity in neutron stars in general and the superfluid moment of inertia fraction for pulsar glitches in particular using the precision pulsar timing technique of the SKA.

The Indian Neutron Star Community has tremendous expertise in theoretical modeling of the EoS of dense matter and mass-radius relationships of (non)rotating neutron stars and will contribute immensely in the science programme of the SKA.

3.2 EOS constraints from thermonuclear bursts

Thermonuclear X-ray bursts are observed from neutron star low-mass X-ray binaries. These bursts originate from intermittent unstable thermonuclear burning of accumulated accreted matter on the neutron star surface (Strohmayer & Bildsten 2006). Thermonuclear bursts provide the following methods to measure neutron star parameters, and hence to constrain the theoretically proposed equation of state models of neutron star cores (see Bhattacharyya (2010) and references therein). (1) Continuum spectrum method: fitting of the continuum burst spectrum with an appropriate model can be useful to measure the neutron star radius. (2) Spectral line method: atomic spectral line observed from the surface of a neutron star provides a clean method to measure the neutron star radius to mass ratio (Bhattacharyya, Miller, & Lamb 2006). However, so far a reliable detection of such a line has not been done. (3) Photospheric radius expansion burst method: a strong burst, which shows an expansion of the photosphere, can be used to constrain the mass-radius space of neutron stars (Özel 2006). (4) Burst oscillation method: intensity variation during thermonuclear X-ray bursts, i.e., burst oscillation, provides the neutron star spin frequency with an accuracy usually much better than 1% (Chakrabarty et al. 2003). The fitting of phase-folded burst oscillation light curves with an appropriate relativistic model can be useful to measure neutron star mass and radius (Bhattacharyya et al. 2005; Lo et al. 2013). (5) Millihertz (mHz) quasi-periodic oscillation (QPO) method: mHz QPO, which originates from marginally stable thermonuclear burning on neutron stars, can be used to measure the stellar surface gravity, and hence to constrain the mass-radius space of neutron stars (Heger, Cumming, & Woosley 2007). Given the systematic uncertainties in measurements, a joint application of some of these methods can be very useful to constrain neutron star parameters. Burst properties can be studied with current and future X-ray instruments, including those of the upcoming Astrosat. In its time, only the LAXPC instrument of Astrosat will have the capability to detect burst oscillations. The above mentioned methods will be complementary to the capability of SKA to measure neutron star parameters (Watts et al. 2015).

3.3 Magnetospheric Studies

Despite much careful theoretical and observational efforts, the details of how these rapidly rotating neutron stars radiate is still a mystery. There have been proposed mainly three types of radio emission models:

- *Plasma mechanisms:* Plasma wave energy is converted into escaping radiation via instabilities associated with the modulational processes and 3D soliton collapse.
- *Coherent Curvature Radiation:* Curvature emission is enhanced by the bunching of charges either in streaming-unstable waves or in 1D electrostatic solitary waves. High brightness in these two types of models is due to spatial coherence.
- *Maser mechanisms:* Masers produce stimulated emission of radiation through various phase-coherent means, such as free electron acceleration in wiggler fields.

The keys to the pulsar puzzle lie in a critical understanding of the emission region geometry, and comparing high time resolution measurements of individual pulses and precision, high-sensitivity polarimetry with the quantitative theoretical predictions which can be tested against the data. One limiting step has been the lack of precise data. The pulsar radio emission region is small and it is at an altitude of a few hundred km depending on field geometry. Possibly the extreme antithetical model is one in which the emission is infinitely beamed radiating tangentially to the local magnetic field lines (Gangadhara 2004). It is thought that the radio-loud regions in pulsar magnetosphere are ruled by plasma electrodynamics in a rotating system. The magnetic field is strong enough to constrain the plasma flow to 1D, and for quantum effects such as pair creation and quantised gyro-motion. The induced electric field is strong enough to accelerate charges to very high Lorentz factors. A relativistic plasma within this system emits coherent radiation as a by-product of pair creation and plasma dynamics. Although this hypothesis has gained wide acceptance, it must be tested by measurements using the widest possible bandwidths, the highest possible time resolution and the best possible sensitivity of the proposed SKA.

The measurements that can be made to best address the underlying emission physics are the following -

- *Ultra-wide bandwidth, ultra-high time resolution observations* are critical, because models diverge in what they predict for short time scales and fundamental emitter bandwidths. The emission changes within one rotation period, so we must have the *highest possible sensitivity* to see individual "pulses". We need radio observations which can resolve the dynamic time-scales of the plasma (on the order of $\sim 10^{-7}$ to 10^{-5} s), the intrinsic plasma-turbulent time scales (as short as $\sim 10^{-9}$ s), and reveal the intrinsic bandwidths of the emission.
- *Motion of emission point:* With the advent of long baseline interferometry it is possible to measure the astrometric motion of pulsar emission point with respect to rotation phase (Pen et al. 2014). The relativistic effects such as aberration and retardation (A/R) effects indeed change the locations of emission point coordinates (Gangadhara & Gupta 2001; Gupta & Gangadhara 2003; Gangadhara 2005), and they are much effective in millisecond pulsars compared to the normal ones. To resolve the emission region of a pulsar would require nano- or picoarcsecond imaging, which is challenging to achieve with the existing telescopes.

- *Micro-structure:* Micro-structure (less-ordered intensity variations with time-scales 1 to 500 μs) is seen in nearly all bright pulsars, but no consensus has been reached as to its origins. We suspect that micro-structure is tied to plasma dynamics within the emission region. Large bandwidths are required to separate intrinsic frequency structure from that imposed by propagation through the inhomogeneous interstellar medium, i.e., interstellar scattering. New technology in the form of low-noise decade-bandwidth dual-polarization antenna feeds and associated low-noise amplifiers are required as well as data recording systems fast enough to sample these bandwidths.

- *Polarimetry:* Polarization measurements at high time resolution are a critical component of every approach to understanding pulsar radiation. Wave polarization provides almost all information about the emission geometry and reflects the physics of the emission and/or propagation directly. High sensitivity is absolutely a key because useful polarimetry requires that the received signal level S substantially exceed the noise level N, e.g., $S/N \gg 1$. What determines the linear and circular polarization of a signal? What causes the rapid orthogonal mode transitions in linear polarization, and the rapid sign changes of circular polarization? Are these a signature of the emission process, or a result of propagation in the pulsar magnetosphere?

Resolution of single pulses to the micro-structure level with full Stokes polarization is required to advance our understanding of the pulsar radio emission mechanism and the propagation effects in the pulsar magnetosphere. Although calibration techniques for accurate polarimetry are now well known, attention must be paid to the polarization characteristics of new wideband feed systems to assure that they can be accurately and unambiguously calibrated. To take advantage of these wide bands we will need fast digital "backend" data acquisition systems with high dynamic range to allow interference excision without corrupting pulsar signals in interference-free bands.

A number of scenarios were proposed to explain the new observational class of RRATs. Assuming them to be a completely separate population of neutron stars leads to the conclusion that in such a situation the inferred number of Galactic neutron stars would be totally at variance with the Galactic supernova rates (Keane et al. 2010). An obvious way out of this problem would be to assume that RRATs are simply members of the ordinary pulsar population and could perhaps be connected to them through some kind of evolutionary process. One such the hypotheses is that the RRATs are objects transitioning from normal pulsars to X-ray dim isolated neutron stars (XDINS). Or that they are somehow related to the magnetars. They have also been conjectured to be part of the normal pulsar intermittency spectrum - the case of extreme nulling, which have been shown not to hold much promise recently (Agarwal et al. 2015).

3.4 Fast Radio Bursts

Fast radio bursts (FRB) are a recently discovered (Lorimer et al. 2007; Thornton et al. 2013; Spitler et al. 2014; Ravi, Shannon, & Jameson 2015) class of radio transients which are of very short duration ($\sim$ millisecond), show characteristics of propagation through cold, diffuse plasma, and likely originate at cosmological distances. There are different hypotheses for creation mechanism of FRBs, including super-conducting strings (Vachaspati 2008; Yu et al. 2014), merger of binary white dwarfs (Kashiyama, Ioka, & Mészáros 2013) or neutron stars (Totani 2013), collapse of supra-massive neutron stars (Falcke & Rezzolla 2014), exploding black holes

(Barrau, Rovelli, & Vidotto 2014), dark matter induced collapse of neutron stars (Fuller & Ott 2014), and many others. None of the above hypotheses is established beyond doubt, and the understanding of the physical origin of FRBs remains as an open challenge. Moreover, discovery of more FRBs might lead to better understanding of the intergalactic medium (Zheng et al. 2014).

A theoretical understanding of FRBs, supplemented by a search for new FRBs in existing pulsars surveys, is of significant recent interest. Already, the Parkes FRB triggers are being investigated with the GMRT for their afterglow emissions. Moreover, there is an ongoing project to develop a transient detection system at GMRT (Bhat et al. 2013), which might be very successful to detect FRBs. More details on FRBs and description of activities and interests among Indian researchers can be found in the write-up presented by the 'Transient Science Working Group'.

3.5 X-Ray Binaries

Observations with Astrosat will improve our understanding of neutron stars in X-ray binaries in several ways. The biggest advantage that Astrosat provides is in terms of large effective area of the LAXPC instrument, especially over a wide energy band extending upto 80 keV. Among the known and yet to be discovered LMXBs, Astrosat is likely to discover more accreting millisecond X-ray pulsars, the improved statistics will give better understanding of the mechanism and limits of the neutron star spin-up via accretion in LMXBs. Discovery of more pulsars in the process of spinning up in LMXBs, like the 11 Hz accreting pulsar in the globular cluster Terzan 5 will be additional support for the process of spinning up of neutron stars through their LMXB phase. Observations of the KHz quasi-periodic oscillations, thermonuclear burst oscillations, and thermonuclear burst spectroscopy are also likely to be significantly improved with Astrosat. All of these are very useful for understanding the EOS of neutron stars.

Astrosat will carry out a lot of study of the high magnetic field accreting neutron stars, more commonly known as accreting X-ray pulsars, most of which are found in HMXB systems. Different aspects of X-ray pulsar studies with Astrosat that are of wider interest are i) magnetic field configuration of the neutron stars, ii) possible alignment of the spin and magnetic axis, iii) magnetic field evolution in the accretion phase. Understanding of these will improve with Astrosat measurements of energy and intensity dependence of the pulse profiles of these systems and pulse phase dependence, luminosity dependence, and time dependence of the cyclotron line parameters of the X-ray pulsars. A type of relatively newly known accreting systems are the fast X-ray transients with super-giant companion stars. Though most of these systems are expected to harbour high magnetic field neutron stars, persistent X-ray pulsations have been detected in only three of these systems and cyclotron line has been detected in only one system. Astrosat observations are likely to bring more clarity to the nature of the compact objects in these systems and perhaps provide insight onto why accretion from wind in these systems give different X-ray features in the form of fast transient outbursts.

4 Gravitational Physics : The pulsar probes

Two key Science goals of the SKA involve exploring the nature of relativistic gravity and to directly detect nano-Hertz gravitational waves, predicted in general relativity. At present, Pulsars in binary systems are extremely successful in testing general relativity in the strong field regime (Stairs 2003; Stairs 2004; Kramer et al. 2006; Stairs 2010). These pulsar binaries usually include neutron star-white dwarf (NS-WD) and neutron star-neutron star (NS-NS) systems. Unfortunately, neutron star-black hole (NS-BH) binaries are yet to be discovered, although different studies on such possible binaries in the Galactic disk (Pfahl, Podsiadlowski, & Rappaport 2005; Kiel & Hurley 2009), globular clusters (Sigurdsson 2003), and near the Galactic center (Faucher-Giguère & Loeb 2011) have been presented. If NS-BH binaries have small orbital periods (around a day), as predicted (Pfahl, Podsiadlowski, & Rappaport 2005; Kiel & Hurley 2009), these might lead to superior tests of general relativity, provided technical difficulties can be overcome. These systems might also help to determine the spin parameter of the BH and test the validity of the *Cosmic Censorship Conjecture* and to test the *BH no-hair theorem* (Shao et al. 2015). As NS-BH binaries are also important sources for gravitational waves for Advanced LIGO, understanding of the properties of these systems from pulsar data analysis will help the gravitational wave community to build better waveform templates.

The orbital dynamics of pulsars in binary systems are generally described in terms of five Keplerian and eight post-Keplerian parameters (Damour & Deruelle 1986; Kopeikin 1994; Lorimer & Kramer 2004). The leading order expressions under general relativity have been used for the post-Keplerian parameters. Measurements of these post-Keplerian parameters (through pulsar timing analysis) lead to the determination of the masses of the pulsar and the companion. For a NS-BH binary, the values of these post-Keplerian parameters will be larger, e.g., the Shapiro range parameter for a NS-BH binary is more than seven times larger than that for a NS-NS binary (Bagchi & Torres 2014). Such high values of these leading order post-Keplerian parameters for NS-BH systems imply that these terms will be measurable even with a shorter data span. Moreover, even the higher order terms might be significant, and if that is the case, one would need to incorporate these higher order terms while performing timing analysis to avoid obtaining inaccurate system parameters (Bagchi 2013; Bagchi & Torres 2014).

A NS-BH system will be a very good tool to test the validity of non-conservative theories of gravity, which produce a self acceleration of the center of mass of a binary (Bagchi & Torres 2014). Moreover, within the framework of general relativity and many other theories of gravity, any perturbation in the space-time (like rotating neutron stars or black holes, neutron stars with other compact objects as binary companions, etc.) produces ripples, i.e. gravitational waves. For the case of general relativity, the emission of the monopolar gravitational wave is forbidden by the conservation of mass and the emission of the dipolar gravitational wave is forbidden by the conservation of momentum. The quadrupolar emission remains as the lowest order mode of emission of gravitational waves under this theory. The existence of such emission has been established by measurement of the decrease of the orbital period of many NS-NS and NS-WD binaries. But there are many hypothetical alternative theories of gravity (like the 'scalar-tensor' theories) which allow emission of monopolar and dipolar gravitational waves. NS-BH systems will be better systems to detect such emissions as the combined effect of monopolar, dipolar and qudrupolar gravitational wave emission is much larger for such a system than that of NS-WD systems (Bagchi & Torres 2014). It will be interesting to probe the implications of employing adiabatic precessional equation for the orbital plane in the context of testing the *BH no-hair theorem*. It turns out that going beyond such an adiabatic approximation is relevant while constructing gravitational wave inspiral templates (Gopakumar & Schäfer 2011; Gupta & Gopakumar 2014). Going beyond the above adiabatic approximation can lead to certain quasi-periodic variations of angles that specify the orbit. This is qualitatively similar to quasi-periodic evolutions of few Keplerian parameters while incorporating the effect of gravitational wave emission in a non-adiabatic manner as detailed in (Damour, Gopakumar, & Iyer 2004).

However, a NS-BH system will not be as good as a NS-WD system while trying to probe possible variation in the value of the gravitational constant G or to test strong equivalence principle (Bagchi & Torres 2014). Another interesting possibility will be to observe millisecond pulsar binaries whose companions are visible in the optical and near-infrared wavelengths with large telescopes like the Thirty Meter Telescope in the square kilometer array era. The combined optical and radio observations of such double spectroscopic binaries should eventually allow us to test 'scalar-tensor' relativity theories in certain interesting regime which are at present difficult to achieve (Khargharia et al. 2012).

On the gravitational wave aspect, we plan to pursue investigations that can provide constructs, relevant for analyzing pulsar timing array data, that model gravitational waves from massive spinning black hole binaries in post-Newtonian eccentric (and hyperbolic) orbits. These investigations are expected to be influenced by (Damour, Gopakumar, & Iyer 2004; Tessmer & Gopakumar 2007; Gopakumar & Schäfer 2011; De Vittori et al. 2014) that provided accurate and effect prescription to construct post-Newtonian accurate gravitational wave templates compact binaries in non-circular orbits.

The fast spinning accreting neutron stars with an accretion mound are potential sources for the ground based gravitational wave detectors (Bildsten 1998). These sources are attractive due their spin frequency being several hundred hertz, a match with the GW detectors. At the same time, gravitational wave search from these sources are very computation intensive because its detection will require coherent analysis of data over a long period of time, a couple of years. One needs to know the spin and orbital parameters of the system and their evolution very accurately over this entire period. Otherwise, the parameters space for search is very large (Watts & Krishnan 2009) rendering it impossible and it will also reduce the significance of any detected signal. The spin and orbital evolution of a few accreting millisecond pulsars are known (Hartman et al. 2008), but unfortunately, these systems are transient, and therefore have lower average mass accretion rate, aka weak gravitation wave signal. Some transient sources, like EXO 0748-676, can however, be very potential candidate as they spend long periods in X-ray bright state and go into quiescence in between. If SKA finds radio pulsations from some of these sources in quiescence (same as the the transitional LMXBS), which will also help establish the orbital parameters, gravitation wave searches can be done over relatively smaller parameter ranges during their future X-ray bright states.

5 Multiwavelength Studies

Though the immediate emphasis of this document has been the impact of SKA era on neutron star research, we need to remember that a large number of other high-sensitivity instruments (both in radio and higher energies) are also upcoming; many of which has active Indian participation (like, SKA, TMT, LIGO etc.). It is imperative that maximal advantage is taken of the science capabilities of these. In tables [1] & [2] we present a comprehensive list of such instruments and note down the particular kind of investigations that could be undertaken using them.

6 Summary

It is noted that the interests, of the neutron star community in India, that correspond closely to the SKA science goals (in regard to pulsar astronomy) are as follows -

Table 1. Pulsar studies with high sensitivity ***Radio Telescopes***

	Name & Location	Type	Operating Frequency†	Pulsar Studies*	Remarks
1	Arecibo Telescope, Puerto Rico	Single dish	0.3–10 GHz	1, 2, 3	The world's largest single-dish; 305 m
2	Parkes Radio Telescope, Australia	Single dish	0.7–26 GHz	1, 2, 3	64 m dish
3	GBT, Green Bank, USA	Single dish	0.29–115.3 GHz	2, 1, 3	World's largest (100 m) fully steerable single-dish
4	Effelsberg Telescope, Germany	Single dish	0.4–95 GHz	2, 1, 3	100 m dish
5	Lovell Telescope, England	Single dish	0.4–6 GHz	1, 2, 3	76 m dish
6	GMRT, Pune, India	Interferometer	150–1420 MHz	3, 1, 2	30 dishes (45 m); largest telescope at meter wavelengths, SKA pathfinder
7	Nancay Radio Telescope, France	Kraus-type design	1.1–3.5 GHz	1, 2	single-dish antenna equivalent to that of a 94-m-diameter parabolic dish
8	LOFAR, (mainly) Netherlands	Dipole array	10–240 MHz	3, 1, 2	Low frequency array of crossed-dipole antennas at 1.25 to 30m wavelengths
9	Ooty radio telescope, India	Cylindrical Paraboloid	326.5 MHz	3, 2	530 m × 30 m paraboloid
10	Gauribidanur telescope, India	Dipole Array	34 MHz	3, 1	640 dipoles in East-West direction (originally 1000 dipoles in in a "T" configuration)
11	LWA, Socorro, USA	Dipole array	10–88 MHz	3, 1	256 crossed-dipoles
12	UTR–2, Ukraine	T-shaped dipole array	8–40 MHz	3	Largest telescope at decametre wavelengths (collecting area 150,000 m^2)
13	MWA, Australia	Interferometric	80–300 MHz	3, 2, 1	128× 16-element cross-polar antennas
14	BSA, Pushchino, Russia	dipole array	100 MHz	3	16384 dipoles
15	DKR-1000, Pushchino, Russia	parabolic cylinder	30–120 MHz	3	1000 m × 40 m cylindrical paraboloids (East-West and North-South)
16	HartRAO, South Africa	Single dish	1.66–23 GHz	2	26 m dish
17	WSRT, Netherlands	Interferometer	0.3–8.5 GHz	2	14 dish × 25 ms

*Pulsar studies could be generally linked to primarily three observational kinds — 1: Pulsar searches; 2: Pulsar timing; and 3: Study of pulsar emission mechanisms and interstellar medium properties. The order as well as the main types of studies that have been (or potentially could be) carried out using a particular telescope, are subjective, and entirely a reflection of the author's perception.

†The operating frequency range is nominal, and the observing frequency range may vary depending on the receivers and back-end.

Table 2. Neutron Star studies with ***High-Energy Instruments****

	Mission	Launch Date	Status	Neutron Star Studies
1	Chandra	current		Accurate position/identification, faint source flux measurement, high resolution spectroscopy
2	XMM	current		Iron line shape, high resolution and high throughput spectroscopy, M/R from line during bursts
3	Fermi	current		Frequency evolution, accretion torque, magnetar outbursts
4	Integral	current		HMXB outbursts, Cyclotron line evolutuion, Highly absorbed systems
5	MAXI	current		Monitoring of accreting NS systems, excellent orbital coverage for spectral study of bright sources
6	NuStar	current		Cyclotron line - new sources, better spectral measurement
7	Suzaku	current		Cyclotron line, broad band spectroscopy
8	Swift	current		Supergiant Fast X-ray Transients, All sky monitoring in Hard X-rays
9	Astrosat	2015	approved	Cyclotron line, KHz QPOs with large area and broad energy coverage
10	Astro-H	2016	approved	Highest resolution spectroscopy, plasma diagnostics, cyclotron lines, broadest band (NuStar++)
11	NICER	2016	approved	NS EOS, soft X-ray spectral and timing studies with large area
12	eRosita		approved	Medium energy X-ray survey, new members/population of sources? More magnetars?
13	HXMT	2017?	approved	
14	Loft	$\sim$2025	potential	NS EOS and Strong Gravity
15	Athena	$\sim$2028	approved	
16	Polarimeters		potential	Magnetic field structures, emission mechanism in accreting and young NS.

*Authentic list of current and past observatories are at `http://heasarc.gsfc.nasa.gov/docs/observatories.html`

a) ns population and its' evolutionary connections,
b) properties of super-dense matter (EoS studies),
c) magnetospheric studies, and
d) gravitational wave astronomy.
The Indian community proposes to begin theoretical calculations/simulations as well as design observational projects that would prepare the community to take appropriate use of SKA capabilities. In particular, with the uGMRT being given the SKA pathfinder status it has become imperative to begin designing such experiments.

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SKA-India Science: Magnetism and Turbulence

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Purpose of this document is to discuss a few key science projects related to "Magnetism and turbulence" that the members from the Indian astronomy community may consider doing with the upcoming radio telescope SKA. This list of projects is neither comprehensive nor that a qualitative study is already done on feasibility of the projects mentioned here. These are based on the literature survey and inputs collected from Indian community. We would like to seek more inputs or discussions from anybody interested. It would be great if experts in different fields quantitatively investigate feasibility of the projects listed here. Rest of the documents are factored in two sections "Magnetism" and "Turbulence". For each of these we discuss the basic techniques and limitations of the existing instruments and outline a few science objectives.

1 Magnetism

Magnetic fields are found to be present at scales as large as the intra cluster medium to the smallest structures in the Galaxy, influencing evolution and dynamics of these systems. Radio observations play a key role in understanding the morphology, origin and evolution of the magnetic fields at all scales. The major probes of astrophysical magnetic fields are the following:

- **Synchrotron Emission:** Relativistic electrons in presence of magnetic fields give rise to non thermal synchrotron emission at radio frequencies. Assuming energy equipartition between the magnetic field and the relativistic particles, one can infer the total magnetic field strength. Moreover, as the synchrotron emission is polarised and the polarisation direction depends on the component of the magnetic field perpendicular to the line of sigh of observation, orientation of the magnetic fields can also be inferred from synchrotron radiation. As polarised intensity is only a few present of the total intensity, high sensitivity and accurate polarisation calibration is required to probe the direction of the magnetic field.

- **Faraday Rotation Measure Synthesis:** Propagation of linearly polarised radio waves through the magneto-ionic medium causes rotation of the plane of polarisation due to Faraday effect. Line of sight component of the magnetic field of a magneto-ionic medium can be traced by measuring the linearly polarised flux from background sources. Effectively, if wide bandwidth is used, a three dimensional map of the magneteto-ionic medium can be inferred provided the morphology of the medium can be assumed.

- **Zeeman Effect:** Zeeman effect is splitting of spectral lines in presence of high magnetic field. Using this method magnetic fields of high intensity can be traced against the H I, OH etc spectral lines. This gives a direct probe of the in-situ magnetic field and requires high spectral and spatial resolution.

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In general the major limitation of the present day telescopes for all the above techniques is in the high sensitivity needed for the required resolution. Since most of the cases the emission is localised, at lower resolution it is smoothed out. Moreover, interferometers lack adequate baseline coverage for higher baselines resulting lower sensitivity at highest resolution. Faraday rotation measure synthesis requires wide range of continuous frequency coverage, just being available at the existing telescopes. Also, present day calibration techniques do not address the issue of leaking flux with a non-full polar calibration, this would be a critical issue while aiming for higher sensitivity. In case of the spectro-polarimetric studies, required polarisation calibration at < 0.1 % level is also beyond the capabilities of the present telescopes.

For the projects discussed here, we stress mostly on SKA1-Mid array (Band 1 and 2) that is expected to have $A_{Eff}/T_{sys} = 1630$ m^2/K and a largest baseline of ~ 200 km. Later provides a resolution of 0.22 arc sec at 1.4 GHz (Ska telescope document). All these numbers are almost an order of magnitude better than the existing telescopes. These two bands would provide frequency coverage ranging from 350 MHz to 1.8 GHz with a bandwidth of $700 - 800$ MHz. SKA1-Mid is also attempting to provide full stokes calibration capabilities, though the actual figures of polarisation sensitivities are not clear yet.

1.1 Science Projects

Filaments of Cosmic Magnetic Field

A few pilot surveys has been proposed using JVLA and GMRT (Mao et al. 2014) to map the radio sky by polarised intensity. This is to trace the cosmic magnetic fields, particularly its filamentary structures, its formation and evolution over cosmic time. This requires multi wavelength observations of a few square degrees in the sky with a few nJy sensitivity and < 0.1 % accurate polarisation calibration (Taylor et al. 2015). It would be possible with the SKA1-Mid Band 2 to probe the cosmic magnetic field till the redshift of 2.

Galaxy Cluster

Galaxy clusters are found to have magnetic fields, their importance in understanding the physical processes in the intra cluster medium is also recognized. Several large scale (few Mpc) features from the clusters have already been detected (Bagchi et al. 2002, Giovannini et al. 2010 etc.) with surface brightness of the order of few tens of nJy/arc sec^2 at 1.4 GHz. Central region of clusters often host diffuse radio halo of non thermal synchrotron emission (Carilli & Taylor 2002, Govoni & Feretti 2004) with intensity strongly correlated with the X-ray luminosity, and hence the mass of the cluster. Resent simulation of Govoni et al. (2013) suggests that the halos have intrinsically polarised emission which can be traced when observed at high resolutions (100 pc or lower). Emission in the total intensity itself is quite weak for these emission (1μ JY/ arc sec^2 at 1.4 GHz) and the polarised intensity is not detected yet owing to its cancellation at the present observed resolution. SKA1-Mid at 1.4 GHz with a resolution of 0.22 arc sec would have the right polarisation sensitivity to observe these (Giovannini et al. 2015).

While synchrotron radiation traces the component of the magnetic field perpendicular to the line of sight of observation, Faraday Rotation Measure Synthesis traces the line of sight component. Using models of the magnetic fields it has been shown that this technique can be used against background radio galaxies for clusters with mass $> 10^{13}$ M$_\odot$ (Bonafede et al. 2015). Moreover, this method would be effective in probing the compressed magnetic fields at the shock fonts from the merging clusters.

Johnston-Hollit et al. (2015) has outlined a technique to investigate the evolution of the intra cluster magnetic fields over cosmic time using their imprint on the tailed radio galaxies.

Probing intricacy in the morphology of the tails requires high sensitivity and resolution. Present day telescopes are limited to observe till a redshift of ~ 0.7,. SKA1-Mid would have the right frequency coverage and sensitivity to push these up to a redshift of ~ 2.

Spiral Galaxies

Rotation measure synthesis is an useful tool to probe the galactic magnetic field. In galaxies the small-scale turbulent fields causes beam depolarisation and the fluctuations of the ionic medium causes Faraday depolarisation across the band. This imprint has been used to infer the magnetic field of the external spiral galaxies (Beck et al 2007.). Shneider et al. (2014) presented a detailed calculation of the physics of depolarisation of synchrotron radiation in the multi layer magneto-ionic medium. This technique with high angular resolution (0.22 arc sec), sensitivity (1.6μJy/Beam) and large bandwidth of SKA1-Mid would be key to infer the morphology of the galactic magnetic field for galaxies to a distance of 14 Mpc with a spatial resolution of 100 pc (Heald et al 2014).

Synchrotron emission from the external spiral galaxies has been used to trace the amplitude of the magnetic field over the stellar disk of the galaxies. Sellwood et al. (1999) have shown that the existence of the high H I velocity dispersion in the extra stellar disk of the spiral galaxies can be produced by extraction of the energy from galactic differential rotation through Magneto-Hydro Dynamic (MHD) turbulence. Mechanisms like magneto-rotational instabilities also predict existence of magnetic fields beyond the stellar disk of the galaxies. Supernova generated relativistic electrons are known to diffuse out with a diffusion length of a few kpc. Hence, investigation of synchrotron emission from the extra stellar disk of the spiral galaxies would shed light on the generation of the galactic magnetic field. Such a field, however, is expected to be weak and hence SKA1-Mid would be the right choice to pursue these project.

Milky Way

Measuring magnetic field in the Milky way serves two fold purposes. Here we can study the structure of the field in great details, from kpc to sub par sec scales revealing the details of the MHD turbulence, effect of magnetic fields on star formation etc. On the other hand comprehensive knowledge of the galactic magnetic field also provides better foreground estimates for extra galactic and cosmological observations.

Zeeman effect measurement of the splitting of H I, OH lines in absorption allow us to trace the local high magnetic fields in the spiral arms. These measurements are presently limited by sensitivity at the observed spatial resolution and could be addressed with the increased figures of SKA1-Mid.

Both the ionised and neutral gas in the InterStellar Medium (ISM) have supersonic compressible turbulent dynamics (Elmegreen and Scalo 2004). Mach number of this turbulence can be probed from the gradient of the polarisation map of the galaxy (Gaensler et al. 2011). Present interferometers are not sensitive to the large scale polarisation structures of our galaxy owing to their reduced sensitivity at small baselines. Single dish telescopes provide a resolution of about half a degree in the sky. SKA1-Mid small baseline coverage with the possibility of calibration of the self signals from the individual antennas would open up the possibility to map the galactic polarised emission and hence the turbulence properties at much higher angular resolution.

Measurement of synchrotron radiation from the molecular clouds is expected to provide a great deal of information about the role of magnetic field in star formation. SKA1-Mid (band 2) would be able to probe such regions with a resolution of 0.01 pc at about 1 kpc distance

(Dickinson et al 2014) along the lines of sights not contaminated by complicated synchrotron emissions.

Rotation measure synthesis with high resolution broadband spectro-polarimetric survey would be possible with the survey mode of SKA with sufficiently high speed. This is expected to provide three dimensional structure of the magnetic field of our galaxy from sub per sec to galaxy scales including the field structure near galactic centre (Haverkorn et al. 2015, Gaensler et al. 2015). Spatial resolution and broadband bandwidth of SKA-survey would be the key to these observations.

2 Turbulence

In this section we discuss the feasibility of using SKA1-Mid for inferring about the observed large scale coherent structures in H I column density, possibly produced by compressible fluid turbulence in the ISM. A Major probe of turbulence are the two and higher point correlations of the observed H I intensity field. For an interferometric array with complete u-v coverage an image based estimator of the two point statistics can be used. Unfortunately, SKA1-Mid, like the existing interferometers, lack full coverage at the higher baselines. A visibility based estimator for the two point statistics has to be used instead. Such estimators are already used in literature and can be adopted directly for SKA. Major advantage of SKA here again is one order of magnitude better sensitivity at larger baselines compared to the existing telescopes.

2.1 Science Projects

Crovisior and Dickey (1981), Green et al. (1993) measured the power spectra of the H I intensity fluctuation in Milkyway, which was found to follow a power law with a power law index of ~ -2.6 at length scales ranging a few pc to 100s of pc. These scale invariant structures have been understood to be the result of supernova driven turbulence in the ISM (Elmegreen and Scalo 2004). Dutta et al. (2013) estimated the power spectrum of the H I intensity fluctation from 18 external spiral galaxies. They found that the power spectra follow power laws at length scales ranging a few 100 pc to 10s of kpc with most of the galaxies having a power law index of ~ -1.6. This dichotomy in the power law index (-2.6 for Milkyway compared to -1.6 for external spirals) is understood by Dutta et al. (2009) as an effect of geometry, where at scales shorter than the scale height of the disk three dimensional structures are probed, compared to the two dimensional structures at larger scales. Owing to the lower sensitivity at high resolution their measurements were limited to > 400 pc scales. This observation raises a couple of questions, what drives the structures at scales of a few 10s of kpc and if the same mechanisms also influence the small scales structures seen in our galaxy. It would be interesting to probe the power spectrum of the H I intensity fluctuation for external galaxies over length scales ranging from a few pc to a few 10s of kpc and establish the link, if any, between the small and large scale turbulence. With the resolution of 0.22 arc sec at 1.4 GHz, SKA1-Mid would be able to probe about 10 pc structures to galaxies at a distance of 10 Mpc.

Velocity dispersion of the H I gas in the galaxy is found to have different trend (Tamburo et al. 2008) within and outside the stellar disk of the spiral galaxies. As major component of the dispersion is because of turbulence, it is possible that the origin of the turbulence is different inside and outside the stellar disk of the galaxy. This should show up if the power spectrum of the H I could be measured within and outside the stellar disk separately. With SKA1-Mid, it would be possible to develop a technique to pursue this investigation.

Acknowledgment

This document has been created with inputs from the group members of the SKA. We particularly thank Dr. Aritra Basu for providing valuable comments while preparing the manuscript.

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Heald 2014 (SKA key science projects)

Square Kilometre Array – India: Continuum Surveys Science Working Group

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1 Overview

This report is organised as follows. Sections 2 to 16 list the topics that are taken up as research subjects by various groups in several institutes across the country. Each section presents a brief overview, followed by motivation, and eventually leading to what can be achieved once the Square Kilometre Array (SKA) is made available to the community.

2 Evolution of Star-Formation and Measuring Star-Formation Rates

Star-formation rate evolution has been systematically studied mostly with rest-frame UV data with the *Hubble Space Telescope* (*HST*) and ground based telescopes for nearly two decades. We have been interested in this area from the UV perspective (*e.g.* Wadadekar et al. 2006). Given the large amount of high-sensitivity, high-resolution data that will become available with the SKA, we would be interested to study this subject using SKA radio data, since it is much less affected by dust, and complements UV observations and our earlier studies.

2.1 Origin of Radio−FIR Correlation

The luminosity at a radio frequency ($L_{\rm radio}$) is seen to strongly correlate with the monochromatic and / or bolometric luminosity in the far infrared (FIR) bands ($L_{\rm IR}$) for star-forming galaxies (see *e.g.*, Condon 1992, Yun et al. 2001, Bell 2003, Ivison et al. 2010 and the references therein). The correlation spans over 5 orders of magnitude for galaxy integrated luminosity in both the bands with dispersion less than 50%. The radio–FIR correlation is one of the tightest known correlation in astrophysics that connects several physical parameters of the interstellar medium (ISM).

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The correlation is known to hold for a large range of scales, few 10s of kiloparsec (in the case of galaxy integrated luminosity) to few 10s of parsec to few kiloparsec (for spatially resolved studies). It holds true for a wide morphological type of galaxies ranging from dwarf irregulars (Price & Duric 1992, Chyży et al. 2011, Srivastava et al. 2014, Jurusik et al. 2014) to grand design spirals (Yun et al. 2001, Dumas et al. 2011, Basu et al. 2012, Tabatabaei et al. 2013)

Based on empirical relations, the radio–FIR correlation is thought to originate due to the inter-connections between star formation rates, gas density, magnetic field and energy spectrum of cosmic ray electrons (see *e.g.*, Helou et al. 1993, Niklas et al. 1997b, Volk 1989). Due to recent advances in our understanding of magnetic field amplification in galaxies, it is now abundantly clear that in the heart of the correlation lies the coupling between magnetic field strengths (B) and gas density ($\rho_{\rm gas}$) of the form $B \propto \rho_{\rm gas}^{\kappa}$ (Groves et al. 2003, Schleicher et al. 2013, Lacki et al. 2010, Thompson et al. 2006).

The radio–FIR correlation is characterized by two quantities: 1) the slope in log-log space, b defined as $L_{\rm radio} \propto L_{\rm IR}^{b}$ and 2) the quantity 'q' defined as $\log_{10}(L_{\rm IR}/L_{\rm radio})$. The slope b is observed to be non-linear for spatially resolved galaxies (Basu et al. 2012, Dumas et al. 2011, Tabatabaei et al. 2013, Hughes et al. 2006). However, for global studies the slope is seen to be close to unity (Yun et al. 2001, Condon 2002, Helou et al. 2005). In the case of linear correlation, the quantity 'q' is expected to be a constant and its spread in an indicator of the tightness of the correlation. However, if the slope is non-linear, 'q' depends on the slope and the radio or infrared luminosity and cannot be considered to be a constant. Slightly non-linear slopes has been reported in the literature earlier for global studies like, Bell et al. (2003), Price & Duric (1992), Niklas et al. (1997). It is therefore important to establish the slope of the correlation at higher redshift with larger sample of galaxies in various redshift bins.

Recent theoretical interpretation given by Schleicher et al. (2013) indicate a change in the form of the correlation with redshift (z) owing to the evolution of the ISM parameters. Note that the evolution of star-formation rate, inverse-Compton losses, spectral energy distribution of galaxies, magnetic field strengths and amplification mechanism with redshift can affect the form of the radio–FIR correlation, both slope and the parameter 'q'. They may eventually lead to breakdown of the correlation at higher redshifts. Schleicher et al. 2013) predicted a critical redshift (z_c) given by,

$$z_c + 1 = \left(\frac{\Sigma_{\rm SFR}}{4.5 \times 10^{-3}\ M_{\odot}{\rm kpc}^{-2}{\rm yr}^{-1}}\right)^{1/(6-\epsilon/2)} \tag{1}$$

at which the radio–FIR correlation is expected to break down. Here, $\Sigma_{\rm SFR}$ is the star-formation rate surface density and ϵ describes the redshift evolution of mean ISM density ($n_{\rm ISM}$) as

$$n_{\rm ISM} \propto (1+z)^{\epsilon}. \tag{2}$$

A change in the slope of the correlation is also possible depending on the dominant energy loss mechanism of the cosmic ray electrons in the radio domain, *i.e.*, synchrotron, inverse-Compton, bremsstrahlung and / or ionization losses. It is therefore important to explore the nature of the radio–FIR correlation observationally to understand its origin and its eventual breakdown at high redshifts.

Moreover, studying the correlation at higher redshifts has cosmological implications in terms of magnetic field amplification across peak epoch of galaxy evolution. Note that the parameter 'q' has been observed to vary with redshift as, $q \propto (1+z)^{\gamma}$, where γ is observed to be -0.15 ± 0.03 (Ivison et al. 2010a) and -0.18 ± 0.10 (Bourne et al. 2011). This indicates enhanced radio emission from normal galaxies as compared to FIR emission at higher redshifts and thereby giving rise to radio background. Also, for the correlation to hold true at higher redshifts with respect to what is observed for local galaxies, synchrotron losses should dominate over inverse-Compton losses. This requires the magnetic field strength to grow with redshift as

$$B_c \sim 3.2(1+z)^2\ \mu\text{G} \tag{3}$$

(Schleicher et al. 2013) leading to significantly stronger field strengths (Murphy et al. 2009). Here, B_c is the equivalent CMB field strength. This would help us understand magnetic field amplification mechanisms at earlier epochs.

Given the available sensitivity of a few μJy, the current radio telescopes can detect normal Milky Way type star-forming galaxies up to a redshift of ~ 0.2 at 1.4 GHz. At higher redshifts ($z \gtrsim 0.5$) one detects (ultra) luminous infrared galaxies ([U]LIGRs) (Appleton et al. 2004, Sargent et al. 2010, Mao et al. 2011, Del Moro et al. 2013). Such objects are often known to have extreme ISM conditions and results based on them are difficult to interpret when compared to normal galaxies. Several recent studies in the literature have employed the technique of image stacking to detect normal galaxies at higher redshifts (Ivison et al. 2010, Bourne et al. 2011). Such a technique trades off sample size and allows one to study only the mean properties of the sample. It is therefore imperative to characterise the correlation for normal galaxies with large number of direct detections in moderate redshift bin sizes of $\sim 0.1-0.5$ up to $z \sim 2$. This requires advanced next generation radio telescope having high sensitivity. The SKA would be an ideal instrument to enhance our understanding of the radio–FIR correlation and its possible evolution / breakdown at higher redshifts as predicted based on the theoretical arguments (Murphy et al. 2009, Schleicher et al. 2013).

Multi-object spectrographs on large optical telescopes are now routinely producing samples of hundreds of thousands of galaxies (*e.g.*, Coil et al. 2011 [PRIMUS]; Guzzo et al. 2013 [VIPERS]; Newman et al. 2013 [DEEP2]; Le Févre et al. 2005 [VVDS]; Baldry et al. 2010 [GAMA]). Such surveys can be easily used to classify various galaxy types based on ISM properties and morphology. With the upcoming SKA, the radio–FIR correlation can be studied in detail up to a high redshift for each galaxy type and throw meaningful insights into our understanding of the radio–FIR correlation.

In addition, we have often used stacking techniques in radio, mid and far-infrared to study the evolution of the radio-FIR correlation in quiescent star-forming galaxies to $z \sim 1$. With SKA sensitivities, these studies could be carried out without stacking, through direct detections.

3 Normal Galaxies

Galaxies are collections of stars, dust and gas. They usually contain $\sim 10^6$ to over a $\sim 10^{12}$ stars. Their sizes can range from a few thousand to several hundred thousand kilo-parsec across. There are $\sim 10^{11}$ galaxies in the universe. Galaxies vary in size, structure, and luminosity, and, like stars, are found isolated, in pairs, or in clusters. Galaxies are divided into three basic types: spirals, ellipticals and irregulars. Below we list a few key science projects with regard to these normal galaxies, and why SKA is important for them.

1. Low Surface Brightness (LSB) Galaxies : These are gas rich, low luminosity spiral galaxies. One of the main findings of our optical studies on LSB galaxies is that the bulge dominated large LSB spirals host weak AGN activity that these are associated with low mass black holes (BHs) which lie below regular galaxies on the $M-\sigma$ correlation. These nuclear supermassive or intermediate mass black holes may represent a population of 'pristine' un-evolved BHs. Giant Metrewave Radio Telescope (GMRT) radio continuum studies show that their AGN often show compact radio emission and sometimes radio jets.

2. Void galaxies : Deep optical surveys have revealed that voids contain a sparse but significant population of galaxies. These void galaxies show signs of moderate star formation and even AGN activity. The main aim of our study is understanding how the star formation process and galaxy evolution in these isolated systems is related to the void environment. Radio continuum mapping of void galaxies will help us understand star formation and AGN activity in these galaxies.

3. Double AGN in nearby galaxies : Dual or binary supermassive black holes will form due to galaxy mergers or accretion events. However, it is very difficult to detect such systems optically as dust obscuration and resolution limit our seeing. Radio continuum observations have been able to detect several double AGN in quasars, but the detection rate is still fairly low. Further radio continuum surveys coupled with x-ray studies will be able to help us understand the frequency of double nuclei in galaxies and their role in the evolution of galaxy nuclei.

Why is SKA important ?

1. The resolution and sensitivity of the SKA will help us detect weak AGN in low luminosity systems.

2. It will help us map the large scale structure (LSS) and search for signatures of star formation and galaxy evolution in these sparse regions.

3. The resolution and sensitivity of the SKA will enable us to detect a much larger number of dual AGN.

4 Large-Scale Structure of the Universe

The existence and dominance of dark energy and dark matter remain the biggest puzzles in the concordance cosmological model. Astrophysical observations of large scale structure are our best bet to develop a phenomenological understanding of these two components. During the last few years we have been involved in development of methods that constrain cosmological parameters such as the matter density parameter, $\Omega_{\rm m}$, the amplitude of fluctuation, $\sigma 8$, and the dark energy equation of state using galaxy observations. In particular, we have explored the synergy between the clustering of galaxies and their weak gravitational lensing signal. In this regard, our research has focussed on data from relatively low redshift surveys such as the Sloan Digital Sky Survey and the CFHT Legacy Survey.

The capability of SKA to conduct a survey of neutral hydrogen in galaxies out to $z = 1.5$ will be a huge game changer. We are interested in detection of the baryon acoustic feature in the clustering of galaxies, which acts as a standard ruler. This will allow us to perform cosmic cartography in order to probe the geometry of the universe. The sample variance errors will be greatly reduced due to the large volume which will be surveyed.

In addition to the above geometric probe, we are also interested in the growth of structure measurements which will be possible by combining the clustering of galaxies and their weak gravitational lensing signal. The latter signal can be obtained using the SKA either by looking at the shapes of faint background galaxies or by cross-correlation with the precise measurements of the cosmic microwave background. Growth of structure measurements are crucial to distinguish between dark energy and modifications of gravity, which are the two models competing to explain the mysterious expansion of the universe.

4.1 Galaxy Clusters and Groups

Studies of galaxies and their locations in universe suggest that they tend to form in groups called clusters of galaxies (see also Section 6). Depending on the number of galaxies within the cluster, these clusters may be classified as rich (containing $\sim 10^3$ of galaxies) or poor. Similar to morphological classification of the galaxies, clusters may also be classified as regular or irregular depending on the overall shape of the cluster.

From a theoretical astrophysicist's perspective, with current research interest in thermodynamics of galaxy cluster cores, physics of accretion and jets, and galactic outflows. Most recently we have concentrated our efforts on understanding the physics of X-ray emitting galaxy cluster cores, which should cool rapidly if not for energy deposition due to AGN jets. We have developed a picture of cluster cores which are in rough thermal balance, but can become locally thermally unstable when the core density increases beyond a threshold corresponding to the ratio of the local cooling time and the free-fall time becoming less than about 10. With simulations of feedback AGN jets we have verified this criterion. We also observe cooling and AGN heating cycles in cluster cores in our simulations.

Galaxy clusters emit in most wavebands, and are among the most important sources of diffuse synchrotron radiation. In addition to the jets and bubbles blown by supermassive black holes at the centre, other forms of diffuse radio emission is observed in several galaxy clusters: compact radio mini-halos, radio halos, and relics. While a mini-halo is associated with a cooling core of a relaxed cool-core cluster, radio halos and relics are associated with mergers (see also Section 6.5.2, 6.5 and 6.5.1).

SKA with its unprecedented sensitivity, is expected to help understand all forms of radio emission from galaxy clusters. Currently the detection of halos and mini-halos is hampered by low sensitivity. With more complete samples we should be able to ask if (and how) energetic protons associated with mini-halos play any role in quenching of the cooling flows in cluster cores. The observed bimodality in the correlation between X-ray luminosity and radio halo luminosity is commonly attributed to mergers; *i.e.*, the systems undergoing mergers accelerate particles that power radio halos. However, there are several cluster with a disturbed X-ray morphology and with no radio halo. SKA will tell us whether such a bimodality is real or an artefact. SKA will improve the rotation measure mapping of magnetic field strength and geometry in galaxy clusters, and its variation with radius.

SKA has the potential to unveil the role of non-thermal components (magnetic fields and energetic particles) in galaxy clusters, which are currently not considered so widely. These components can be of paramount importance both in core thermodynamics and in cluster outskirts, where it is essential to model the non-thermal pressure support in order to use clusters as cosmological probes.

4.2 Galaxy Formation and Evolution

In addition to cosmology (Section 4), in the area of galaxy formation and evolution, SKA can probe the gas reservoirs in galaxies and their evolution since high redshift. Rather than looking at very complex semi-analytical models of galaxy formation and evolution, we are interested in developing simpler phenomenological models of how these gas reservoirs get converted into stars. For example, models which rely on the sub-halo abundance matching technique have been very successful in distilling the information about the relation between galaxies and their dark matter halos see also Section 6. Such information has been very constraining for semi-analytical models of galaxy formation. One can use similar methods to understand the evolution of the gas within dark matter halos and contrast it with the evolution of stellar mass.

5 Fanaroff-Riley Dichotomy and Radio-Loud Unification

Bernard Fanaroff and Julia Riley first pointed out that kiloparsec-scale jets in radio galaxies exhibited primarily two radio morphologies: the Fanaroff-Riley (FR) type I galaxies had broad jets that flared into diffuse radio plumes / lobes, while the FR type II galaxies had collimated jets that terminated in regions of high surface brightness called "hot spots" with the back-flowing plasma or plasma left behind by the advancing jet forming the radio lobes (Fanaroff & Riley, 1974). The total radio power of the FR I / FR II sources also differed: the dividing line at 178 MHz was at $L_{178} \simeq 2 \times 10^{25}$ W Hz^{-1}, with the FR II sources being the more powerful ones. Due to the presence of relativistic jets and obscuring dusty tori, the same type of AGN could look drastically different with respect to radio morphology and emission line spectra. The radio-loud unified scheme proposes that BL Lac objects are the pole-on counterparts of FR I radio galaxies while the radio-loud quasars are the pole-on counterparts of FR II radio galaxies. BL Lacs and quasars are collectively referred to as blazars.

We examined the Unified scheme and the FR dichotomy in the MOJAVE[1] sample of 135 blazars using high-resolution 1.4 GHz data from the Very Large Array (VLA) in Kharb et al. (2010). We found that a substantial fraction ($\approx 20\%$) of MOJAVE quasars and BL Lacs had radio powers that are intermediate between FR Is and FR IIs. Many BL Lac objects had lobe luminosities ($\approx 30\%$) and hot spots ($\approx 60\%$) like quasars. These findings challenged the simple radio-loud unified scheme. In addition we found a strong correlation between the kiloparsec-scale lobe luminosities and parsec-scale jet speeds: the large-scale jet and lobe emission knew about the small-scale jet as it was launched. It therefore appeared that the fate of the AGN was decided at its birth. All these results need to be re-examined with much more sensitive radio data, as will become available with the SKA.

Sensitive SKA observations at low frequencies (≤ 1.4 GHz) will be able to detect the full extent of the diffuse lobe emission in radio galaxies and blazars. In addition these sensitive data will become available for a much larger population of radio sources including the so-called "core-only" sources ($\approx 7\%$ in the MOJAVE sample). With SKA low-frequency data we will be able to re-examine the issues of the FR dichotomy and radio-loud unification to a much higher significance than has been done before.

6 AGNs: Quasars and Radio Galaxies

In 1960 a peculiar radio source was discovered, and this one turned out to be a "star" with emission lines, which are due to Hydrogen and were extremely redshifted. This quasi-stellar radio source would become known as a "quasar". There seems to be a vast difference in activity when comparing quasars to normal galaxies. This difference can be filled in with active galaxies such as Seyfert galaxies and radio galaxies. Quasars and radio galaxies are extensively used to explore the cosmic web and to understand the large-scale structure of the universe (see also Section 4). Below we list some of the research subjects, which would be studied using SKA.

6.1 Different Morphologies of AGNs and their Ambient Media

We have studied several field and cluster radio galaxies of different morphological forms at low radio frequencies using GMRT. Our prime aim has been to detect faint radio emission at very low frequencies due to low energy electrons. The results provide evidence that the spectra of low-surface-brightness features are flatter than the spectra of high-surface-brightness features in several sources found in field as well as cluster environments (see also Section 4.1 and

[1]Monitoring of Jets in AGN with VLBA Experiments (Lister et al. 2009). http://www.physics.purdue.edu/MOJAVE

10). In addition, the low frequency radio images of field galaxies show morphologies that are similar to the morphologies at high frequencies. These results suggest that the low-frequency synchrotron emission in field galaxies fades (nearly) as rapidly as high-frequency synchrotron emission and that synchrotron cooling is not the dominant energy-loss mechanism for the plasma out of which radio lobes are composed in field galaxies. Whereas, for radio sources in cluster environments, synchrotron cooling and possibly, inverse-Compton cooling are the dominant energy-loss mechanisms. Additionally, simple picture of spectral ageing needs revision.

High resolution and high-sensitive *Chandra* archive have a large amount of data for FR II and X-shaped radio galaxies (see Section 5). Using the sensitive SKA data at large range of frequencies, we propose to perform systematic inverse-Compton analysis, including the upper limits on the lobe X-ray emission where there is no detection, and thereby set limits on the lobe magnetic field strengths to understand the nature of X-shaped radio sources using our control sample of FR II galaxies (Lal et al. 2007, 2008). We plan to test the models for the sample of X-shaped sources by correlating the intra-cluster medium (ICM) distribution with the wings and the lobes. We intend to search for asymmetries, which are signatures of the radio plasma of the wings being re-energised by the shock in the ambient medium on spatial scales of the wings. This forms the key test for the hydrodynamic model to remain viable in light of the flatter spectral index of the faint features.

6.2 Giant Radio Galaxies

Giant radio galaxies can be used as the pointers of black hole physics and the 'barometers' of the intergalactic medium in the cosmic-web. Here, the aim is to use the radio galaxies to explore the cosmic-web and the large scale structure of the universe (see also Section 4).

Giant radio galaxies (GRGs), whose non-thermal plasma lobes span $\sim$1 Mpc (mega-parsec) or more are among the largest, most luminous, yet the least understood enigmatic objects in the universe. Majority of GRGs show edge- brightened FR-II (see Section 5) morphology having linear sizes well beyond the interstellar medium of the host galaxies. Thus, their lobes expand into the faraway low density ambient medium, rendering them as excellent probes of the large scale cosmic-web structure of the universe. Due to sensitivity limitations of the present large radio telescopes like the JVLA or GMRT, most of the GRGs found so far are in the nearby universe ($z \lesssim$0.7). Next generation radio telescopes like LOFAR or SKA having extremely high sensitivity will be required to discover many more GRGs (see also Section 6.2.1), that hitherto lie below the detection threshold in the early universe ($z \gtrsim$0.7), thus providing a deep understanding of their evolutionary properties. It is still unknown if the large sizes of GRGs reflect the high efficiency of radio jets depending on the central black hole properties, such as the mass, spin and mass accretion rate of the black hole, or whether they grow to such enormous sizes due to their favourable position within an especially low density ambient medium. Approximately half of the baryons in the present day universe are still unaccounted for ('missing'), in the sense that these baryons are believed to reside in the large galaxy filaments, in the form of Warm-Hot Intergalactic medium (WHIM), as part of the cosmic-web structure of the universe. The large extents of GRGs provide an excellent opportunity to use them as 'barometers' for probing the physical properties of this WHIM gas (its temperature, pressure and magnetic field). For this purpose a sensitive search using SKA and LOFAR for Mpc scale radio sources in the vicinity of galaxy filaments and perhaps inside the voids, surrounded by sheets of galaxies would be extremely interesting.

6.2.1 Discovering Giant Radio Galaxies and Double-Double Radio Galaxies

Radio galaxies are best known for their extensive double radio sources, shining by synchrotron radiation as electrons spiral through magnetic fields at relativistic speeds. Similarly, Double-Double Radio Galaxies (DDRGs) offer a unique opportunity for us to study multiple episodes of jet activity in large-scale radio sources. In the *XMM*-LSS field, we have a discovered a new Mpc sized radio galaxy at $z = 1.32$. This object also show evidence of episodic activity as well as inverse Compton scattered X-ray photons. At the present time, such high redshift objects are rare and difficult to find. With SKA, such discoveries and discoveries of many kinds of radio galaxies will be routine and we will focus on the statistical properties of large samples rather than studying individual objects (see also Section 6.2).

6.2.2 Powerful Radio Jets on $\sim 0.1 - 1.0$ Mpc Scale

Another related problem that can be addressed by sensitive SKA and LOFAR searches is the detection of powerful radio jets on ∼0.1–1.0 Mpc scale in high redshift radio galaxies and quasars (see Section 13 for a discussion on jets in radio-quiet AGNs). Though radio galaxies a few 100 kiloparsec in extent are common at z of 1–2, comprising 10% of the most powerful AGN, at higher redshifts, they are very rare, with no radio galaxy or quasar above few tens of kiloparsec known above redshift $z \sim 4$. This is a mystery as the redshift evolution of powerful AGNs with radio jets indicate that they may constitute a larger fraction of the AGN population above redshift 2 than that appears from the number of detected GHz radio sources in present surveys. Some of the beamed sources in this class appear as radio loud Blazars. However this radio picture is misleading as the dramatic $(1+z)^4$ boost in the energy density of the CMB causes inverse Compton scattering to dominate the energy losses of relativistic electrons in the extended lobes produced by misaligned jets, making them strong X-ray, rather than radio, sources. Therefore a future combined radio X-ray search targeting extended, double lobed X-ray sources at high redshifts should reveal an 'invisible' population of AGN with large scale radio jets for further studies.

6.3 Morphology of (Head-Tail) Radio Galaxies as Tracers of the Cluster Potential

'Head-tail' sources (Ryle & Windram 1969) are characterised by a head identified with the optical galaxy and two trails of FR I (see Section 5) radio source sweeping back from the head (Miley et al. 1972; Jaffe & Perola 1973). Furthermore, the long tails of these galaxies carry the imprint of relative motion between the non-thermal plasma and the ambient hot gas. Hence, in the parlance of the field, they reflect the weather conditions of ICM, which allows us to make quantitative statements about their dynamics and energetics see also Section 6. The potential of such observations is also to reveal details of cluster mergers such as subsonic / transonic bulk flows, shocks and turbulence. Fortunately, the jets survive the encounter with the ICM, with possible shocks leading to the formation of the long tails, and specifically they seem to be devoid of the growth of Kelvin-Helmholtz instabilities (Loken et al. 1995).

Recently, we conducted a radio study, using GMRT for a sample of head-tail radio sources, concentrating on NGC 1265 and IC 310, which have archive X-ray data, and propose new X-ray observations for objects which are in poor environments where temperature and abundance variations are likely to be more visible in the X-rays. When combined with radio data, these multi-waveband data usually probe: (i) collimation and surface brightness of the jets, (ii) radio jet–ICM interaction, (iii) infall of head-tail sources into the cluster, (iv) details of cluster merger, (v) gas pressure to compare with equipartition pressure, (vi) energy losses, particle acceleration, and (vii) cluster centre ambiguities. This study can easily be extended to large number of weaker, low-surface brightness but extended sources, say in poor clusters and groups, which SKA would easily detect and map in detail.

6.4 Inverse-Compton Emission from Radio Lobes of Powerful High-Redshift AGNs

High-redshift radio galaxies (HzRGs; $z > 2$) are excellent beacons for pin-pointing some of the most massive objects in the early universe, whether these are galaxies, SMBHs (super-massive black holes), or even clusters of galaxies (van Breugel et al. 2003). The strongest constraint on the high-z evolution of SMBHs comes from the observation of powerful HzRGs. The luminosities of these sources, well in excess of 10^{47} ergs s^{-1}, imply that SMBHs with masses $\sim 10^9$ M$_\odot$ are already in place when the universe is only 1–3 Gyr old (Volonteri & Rees 2005). To grow seeds up to 10^9 M$_\odot$ requires an almost continuous accretion of gas. Therefore, to understand the evolution of the first SMBHs into the first pre-galactic radio sources and their impact on the reionization of the universe (Madau et al. 2004), it is important to understand the balance in the energy budget between mechanical and radiative power at these high redshifts.

Advantages of studying inverse-Compton scattering of the CMB in HzRGs: Few good methods exist of measuring the magnetic fields in radio sources (see also 6.5.1). Discussions of the energetics and dynamics of radio sources are often based on the assumption that there is equipartition of energy between magnetic fields and energetic particles (or, effectively equivalently, that the total energy has the minimum value consistent with the production of the observed synchrotron radiation). although this assumption remains difficult to test observationally. Because the emissivity from any scattering process depends upon the number density of electrons (for optical depth $\tau << 1$), it is possible to use *Chandra* observations of this process to constrain the magnetic field in the scattering regions, provided that the synchrotron spectrum and geometry are well known (Hardcastle et al. 1998).

The primary reason that the study of the inverse-Compton scattering off cosmic microwave background process at high redshift is so fruitful is that the energy density of the CMB increases as $(1+z)^4$. Hence, for a high-z radio galaxy (HzRG) the increase with redshift in the energy density of the CMB, combined with its shift to shorter wavelengths exactly compensate for the cosmological dimming and redshift, making the surface brightness (and spectrum) of the inverse-Compton scattering off cosmic microwave background radiation from a fixed population of electrons independent of its redshift. This means that sensitive observations from the SKA, coupled with the high resolution of *Chandra*, can allow us to detect and model inverse-Compton emission from HzRGs as well.

6.5 Diffuse Radio Emission and the Intra-Cluster Medium

Radio emission from clusters is predominantly synchrotron emission from individual galaxies within the cluster. They are characterised by a low surface brightness, large extent $\sim$ 1 Mpc and a steep spectral index. The typical lifetime of diffuse sources is estimated to be of order 10^8 years. Mapping extended, low-surface brightness emission is a challenge. This is because, it could be as large as a Mpc or even larger, thereby forces one to use complex imaging techniques, *e.g.*, mosaicking. Below we list a few science cases, which would be benefited due to SKA.

6.5.1 'Inverse-Compton Ghosts' and Extremely Faint GRGs at Higher Redshifts.

Here, the focus is to perform deep search with SKA and LOFAR for finding 'inverse-Compton ghosts' and extremely faint giant radio sources at higher redshifts.

The boost in the energy of photons of cosmic microwave background (CMB) via interaction with relativistic electrons (the inverse Compton process) strongly affects the observable properties of radio-loud active galactic nuclei (AGN) at early epochs (see also Section 6.4). At high redshifts z, the CMB energy density scales as [$U_{\rm CMB} \propto (1+z)^4$], which can exceed the magnetic energy density ($U_{\rm B}$) in the lobes of radio-loud AGN. In this case, the relativistic electrons cool preferentially by the inverse Compton process, rather than by synchrotron emission (the energy loss via inverse Compton over synchrotron is $U_{\rm CMB}/U_{\rm B}$). This should make more distant sources less luminous in radio and more luminous in X-rays than their closer counterparts. Thus, for some interval of time after the jet activity is switched off the source will appear as a faint radio source before becoming completely radio and X-ray dark. Due to this reason it becomes extremely challenging to find in GHz radio frequencies these elusive so-called 'inverse Compton ghost' radio lobes extended on megaparsec scale, inflated by jets in radio galaxies and quasars. In contrast, in the inner jet and the hotspots regions, where $U_{\rm B} > U_{\rm CMB}$, synchrotron radiation dominates over inverse-Compton on CMB. The decrease in radio luminosity is thus more severe in misaligned (with respect to our line of sight) high-z sources, whose radio flux is dominated by the extended isotropic component. These sources can fail to appear in current flux-limited radio surveys with WSRT, VLA and GMRT, where they are possibly under represented due to sensitivity limits. As the cooling time is longer for lower energy electrons (γ *lesssim* 10^3), the radio luminosity deficit due to the CMB is less important at low radio frequencies. Therefore a population of elusive 'radio-ghost' not detected so far by WSRT, VLA or GMRT could be found by deep low-frequency surveys with LOFAR and the low frequency component of the SKA.

6.5.2 Diffuse Synchrotron Radio Emission in Galaxy Clusters

Galaxy clusters are some of the largest gravitationally bound structures in the universe, and are also bright sources of thermal X-ray emission. Cluster-wide non-thermal radio emission has been detected and has been a topic of study for more than four decades ever since their discovery. This radio emission, which is synchrotron in origin, has a luminosity of $\sim 10^{41}$ erg s^{-1} and is predominantly found only in those galaxy clusters which are very bright (luminosity 10^{45} erg s^{-1}) at X-ray wavelengths. This radio emission arises due to the relativistic electrons ($\sim$ a few GeV) and the magnetic fields ($\sim$ a few μG) in the ICM and is extended over millions of light years, similar to the extent of the hot (10^7 K) and tenuous ($\sim 10^{-3}$ particles cm^{-3}) X-ray emitting gas found in galaxy clusters. Such large scale radio emission has posed challenges to its imaging and its understanding. The basic issues concern the production and sustenance of relativistic particles and magnetic fields over millions of light years. One of the currently popular model invokes cluster mergers to explain the existence of diffuse radio emission in clusters. luster mergers, the most energetic phenomena since the Big Bang, dissipate up to 10^{64} erg during a cluster crossing time ($\sim$Gyr) and are capable of lighting up the cluster radio emission.

Over the last four decades, a large number galaxy clusters were imaged at radio wavelengths ($20-200$ cm) using a variety of synthesis telescopes like the Very Large Array, the Westerbork Synthesis Radio Telescope and the Giant Metrewave Radio Telescope. Diffuse radio emission in the central regions of the cluster (halos) and toward the periphery of the clusters (relics) were detected in about 5% of all and in about 35% of X-ray bright clusters. Their radio spectra are steep. A correlation between the X-ray luminosity of the cluster and the radio power of diffuse radio emission has been detected. Furthermore, a correlation between cluster mergers and the existence of diffuse radio emission has also been found.

There are many selection effects due to which diffuse radio emission in a large number of clusters would have gone undetected. A large fraction of clusters with low X-ray luminosities ($< 10^{45}$ erg s^{-1}) which are likely to harbour low power radio halos would remain undetected due to the current sensitivity limits. In addition, a large fraction of nearby (redshift < 0.1) clusters with large angular extent halos (> 10 arcmin) are likely to be resolved out in many of the existing surveys. Furthermore, the turbulence model of radio emission predicts an exponentially decaying spectra for the diffuse radio emission in clusters. This means that sensitive low frequency ($50 - 300$ MHz) surveys which are capable of imaging extended emission are needed to detect these sources of diffuse radio emission in clusters.

Some of the recently completed telescopes like the LOFAR and the Murchison Widefield Array (MWA) are expected to fill the lacuna in imaging extended, low surface brightness objects at low frequencies (50 - 300 MHz). The low frequency part of SKA to be built in Western Australia, which is a radio-quiet zone, is expected to bring in a revolution in the area of galaxy clusters by being able to image low surface brightness extended objects at unprecedented resolution and sensitivity. The number of known halos and relics is expected to increase by at least a factor of 10 paving the way for detailed studies of origin and sustenance of relativistic particles and magnetic fields in clusters. These studies have implications to cluster mergers and structure formation. Finally, it is expected that SKA-LO (low frequency part of SKA) will also be able to detect weak radio emission expected from large scale filaments formed in structure formation shocks.

6.5.3 Relationship Between Radio Halo, Relic and Cavity Sources in Clusters of Galaxies

Bîrzan et al. (2004), using a diverse sample have found that 1.4 GHz synchrotron luminosity is an unreliable gauge of the mechanical power of radio sources, but low frequency radio luminosity may be a better indicator. We have therefore currently been using GMRT archive data, available for (nearly) all sources listed in Bîrzan et al. (2008), at low frequencies to evaluate mechanical power generated by AGNs and compare it with mechanical power determined via X-ray cavities. Hence, we propose to investigate (i) how was the material driven from central radio source, (ii) physical conditions of the material, (iii) ageing models of these cavities (Omma et al. 2004), and (iv) large changes in magnetic field expected during their radiative lifetime (Churazov et al. 2001, Basson & Alexander 2003).

Next, we propose to use sensitive SKA and X-ray data of the environment of prototype radio relic and halo source in Coma cluster and several such diffuse sources in clusters to quantify departures from equipartition, by estimating equipartition magnetic fields and the energy density in these sources. This would represent a quantum step in the current observational data. Subsequently, I would also be able to obtain a detailed model of the pre- and post-shock radio plasma as well as an independent measure of the shock compression and geometry in each case. This would show how the relic radio emission is related to the spatial structure of the ambient X-ray-emitting cluster gas.

7 Magnetic Fields in Clusters of Galaxies

Celestial objects are magnetized and magnetic fields of significant strength are found everywhere in the interstellar space, and over small and very large scales, in the extragalactic universe. For example, the Earth has a bipolar field of about 0.5 G at its surface, the Sun has magnetic field is of 10 G at the poles, while sunspots on the surface near the equatorial zone of the Sun can have magnetic field strengths of 2000 G. Similarly, a widespread field of $\sim$5 G is present in the Galaxy, fields of $\sim \mu$G are found in the radio emitting lobes of radio galaxies, and similar or weaker strength are detected in the ICM of clusters of galaxies, and in more rarefied regions of the intergalactic space (see also Section 6.5.2).

Although our knowledge of the magnetic field properties in galaxy clusters has significantly improved in recent years, owing to the improved capabilities of radio and X-ray telescopes, our knowledge on cluster magnetic fields is still poor. This is despite that μG level magnetic fields are widespread in the ICM (Govoni & Feretti 2004), and that magnetic fields may play a significant role in the cluster dynamics.

Due to *Chandra* and *XMM-Newton*, the study of cluster magnetic fields has gained a big interest in recent years and there are still many unanswered questions, *e.g.*, (i) are the fields filamentary, (ii) what are the coherence scales, (iii) to what extent do the thermal and non-thermal plasmas mix in cluster atmospheres, (iv) how do the fields extend, (v) what is the radial trend of the field strength, (vi) how does the field strength depend on cluster parameters such as the gas temperature, metallicity, mass, substructure and density profile, (vii) how do the fields evolve with cosmic time, and (viii) finally how were the fields generated (Govoni & Feretti 2004)?

New generation SKA will establish a clear connection between radio astronomical techniques and the improvement in the knowledge of the X-ray sky. The X-ray data along with radio data will provide a more precise knowledge of the X-ray surface brightness of clusters, *i.e.* of their thermal gas density, allowing interpretation of the sensitive Rotation Measure measurements (Govoni et al. 2003). In addition, the detection of synchrotron radiation at the lowest sensitivities will allow the measurement of magnetic fields in very low surface brightness regions of the intergalactic space, and the investigation of the relation between the formation of magnetic fields and the formation of the large-scale structure in the universe (Govoni & Feretti 2004).

8 Accretion, Evolution and Host Galaxy Properties of AGN

AGN are associated with the accretion of material onto supermassive black holes. AGN activity occurs in at least two different modes, each of which may have an associated, yet different, feedback effect upon the host galaxy. The most commonly considered mode of AGN activity is the "standard" accretion mode associated with quasars, called 'quasar-mode'. Another, second mode of AGN activity, in which the accretion of material on to the black hole, which leads to small amount of radiated energy, but can lead to the production of highly-energetic radio jets, has been referred to as "radiatively inefficient", or the 'radio-mode' (also see Best & Heckman 2012). Although it is believed that the radiatively inefficient and radiatively efficient AGN clearly have fundamental differences, but the precise origin of these differences remains unclear (Hardcastle et al. 207, McNamara et al. 2011). In addition, a new developing picture of radio-loud AGN, in which high-excitation radio galaxies (HERGs) are fuelled at relatively high rates in radiatively-efficient standard accretion disks by cold gas, in contrast to low-excitation radio galaxies (LERGs), which are fuelled at relative low rates, through radiatively-inefficient accretion flows, largely by gas associated with the hot X-ray haloes surrounding the galaxy or its group or cluster (Best et al. 2006, Hardcastle et al. 2007). Theoretical simulations, which construct AGN evolution models suggest understanding the evolving feedback role that AGN may play in galaxy evolution is crucial to distinguish roles of these two different accretion modes. Whereas, observationally, at present one of the most interesting results coming out is the almost distinct nature of the accretion rate properties of the LERG and HERG classes, partly consistent with the FR I and FR II sources (see also Section 5) in the nearby universe (Ghisellini & Celotti 2001; Garofalo et al. 2010).

A large data volume at the optical, in particular Sloan Digital Sky Survey has provided a hugh sample of AGN with spectroscopic identifications, whereas presently, in the radio the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty centimetres (FIRST) survey are the only equivalent counterparts. SKA all sky continuum survey is clearly going to change this picture. Spectroscopy has resulted in more accurate redshift determinations used in studies of the RLF and could be used to identify and study the evolution of HERG and LERG radio sources out to higher redshifts. Deep survey images from the SKA, reliable separations of the HERG and LERG populations would also be extremely useful in studies of the role of AGN feedback in shaping the global accretion, evolution and hos galaxy properties of the universe.

9 Evolution of Radio AGN Population

More than three decades ago, AGN represented beacons of light probing the most distant reaches of the universe and were used as tracers of the large scale structure. Once it was realized that there is indeed a strong evolution, *e.g.*, in luminosity, number density, etc. of the AGN population, this early study turned in AGN Demography (Merloni & Heinz 2012). Currently, apart from the "classical" study of AGN luminosity functions, one is also interested in the study of physical relationships between the population of growing black holes and their environment, in particular, how the first black holes formed and the role of black holes in the high-redshift universe.

9.1 Evolutionary History of AGN from the Nearby Universe to the High-z Universe

We have been interested in the search for high redshift ($z > 5$) radio galaxies using the steep spectrum technique (Singh et al. 2014) and their relationship with the AGN in the nearby universe. With current technology, such searches are practical only over small (10 sq. deg) fields. SKA will make such searches trivial over large swathes of sky (see also Section 9).

We are also interested in identifying and studying rare classes of radio AGN, *e.g.* radio galaxies hosted by spiral hosts. Such objects will be trivial to find and study with large area SKA surveys.

10 Environment of AGNs

AGN have have been thought to play a major role in the framework of galaxy formation. During their short lifetime, the enormous amount of energy they produce in the form of ionising radiation or relativistic jets can have a significant effect on their small-scale (internal) and large scale (external) surroundings. Theoretically, it appears that the AGN energetic feedback is a vital ingredient for reproducing some of the observed features of the universe, such as the stellar galaxy mass function (Croton et al. 2005; Best et al. 2006), or the black hole mass versus bulge mass relationship (Gebhardt et al. 2000; Springel et al. 2005a).

The unified scheme gives a good description of the observed properties of radio-quiet AGN. In this picture, the nuclear activity is produced by matter accreted onto a super-massive black hole, with an optically thick dusty torus surrounding it (Antonucci 1993). Best et al. 2005 independently have shown that low-luminosity radio-loud and radio-quiet AGN phenomenon are statistically independent. Many authors have argued that the low luminosity radio-loud and the optically active AGN correspond to two different accretion modes ('Radio mode' *vs.* 'Quasar mode'); see also Section 8.

Additionally, it has often been proposed that galaxy mergers and interactions both trigger a starburst and fuel the central super-massive black hole. In this regard, observations of ultra-luminous infrared galaxies (Sanders & Mirabel 1996) indeed support this merging scenario, that are in general associated with galaxy mergers, and have bolometric luminosities and luminosity function similar to that of quasars (Sanders et al. 1988). Tasse et al. (2007, 2008) using a careful investigation of the intrinsic and environmental properties of radio sources' hosts as compared to the normal galaxy population, show that high stellar mass radio sources are seen to be preferentially located in poor clusters of galaxies, and they further suggest the existence of dichotomy in the nature of both the hosts and environment of radio sources. They further argue that the observed dichotomy might be caused by the different ways of triggering the black hole activity (Tasse et al. 2011).

Therefore, a good way to further test the scheme in which the type of the accretion mode is connected to the nature of the triggering mechanism, is to select AGN based on their X-ray properties. In the picture of unified scheme, the hard X-ray emission is produced in the hot corona that surrounds the black hole, by the comptonisation of soft UV photons which are emitted by the accretion disk (*e.g.*, Liu et al. 2002, Tasse et al. 2011). Finally, to really disentangle this mystery, it is important to have multi-wavelength dataset. Fortunately, very deep surveys of several legacy fields are available in many other wavebands as compared to the radio (see also Section 11), but this is clearly lacking in the radio and in particular deep radio observations at the low-end of the frequency are sparse. With the advent of SKA, it would be easy to perform spectra-energy distribution fits, understand the basic properties of non-radio band selected AGN, etc., thereby provide us with statistical understanding of the environment of AGN.

11 Deep Imaging of Legacy Fields at Low-Radio Frequencies

For several reasons, it is important to discover radio loud AGNs at high redshifts. Firstly, the host galaxies of radio galaxies are among the most massive galaxies, therefore, the formation and evolution of such galaxies at high-redshifts can be studied by picking them through the radio window. This will be complementary to the emerging population of Lyman break galaxy population at high-redshifts, which are less massive by one to two orders of magnitude than AGN host galaxies. Secondly, these objects are known to reside in dense environments, so are excellent tracers of protoclusters. Thirdly, the radio luminosity function of HzRGs beyond redshift of 3 is poorly constrained. It is important to understand whether there is a genuine dearth of HzRGs at $z > 3$ or the observed deficiency is a selection effect. Fourthly, since supermassive blackholes are essential ingredients of radio loud AGN, the formation of supermassive black holes at such early epochs can also be probed using these objects. Therefore, radio loud AGNs are excellent tool to study the cosmological evolution of galaxies.

During late 1970s, while searching for optical counterparts for radio sources a key observation was made, namely that the chance of finding optical counterpart are related to radio spectrum, in the sense that radio sources with normal radio spectrum ($\alpha \sim 0.75$; $S_\nu \propto \nu^{-\alpha}$) had much higher chance of showing optical counterparts as compared to sources with steep radio spectra ($\alpha > 1.3$). Such steep spectrum radio sources for which counterparts were not available at that time, were later shown to be high-redshift radio galaxies. This correlation of radio spectral index vs redshift was exploited to discover a large number of high-redshift radio galaxies (HzRGs) and remains the most successful technique in finding HzRGs.

Despite several decades of efforts only one radio galaxy is known at redshift > 5, though there are close to 50 HzRGs with $z > 3$. The median flux density of all known HzRGs beyond redshift of 3, is 0.5 Jy at 325 MHz. The present day radio telescopes can routinely detect sources down to more than two orders of magnitude than this value, however for $z > 3$, this implies that only reasonably powerful FR II sources will be discovered. Systematic efforts are needed to detect the population of radio galaxies, which are not at the brightest end of the radio luminosity function, but are typical radio galaxies with luminosities near FR I / FR II break luminosity (10^{24} to 10^{26} W Hz^{-1}). It is also interesting to note that recent discovery of a few spiral galaxies with strong radio emission lies in this luminosity range.

Therefore, deep radio imaging beyond the capabilities of current generation radio telescope is needed to discover "normal" population of radio loud AGNs out to redshift of 6. Since the CMBR photon density is much higher at these redshift, the energy loss by inverse-Compton scattering is dominant for relativistic electrons, which will make the life time of electrons that emit at GHz radio frequencies short. For the emission at rest-frame frequency of 1 GHz, it corresponds to observing frequency of a few hundred MHz for $z > 3$ objects. Therefore, to discover the radio loud AGN population as mentioned above, the most suitable telescope is the one which works at low radio frequencies having very low levels of RMS ($= 1\sigma$ noise) and very high angular resolution.

SKA, with its optimum combination of frequency coverage, resolution and many orders of magnitude better sensitivity can detect the above population of radio loud AGNs. More importantly, non-detection of such population also needs to be explained in the context of formation and evolution of AGNs.

11.1 Radio Sky at Micro-Jy Levels

These deep fields represent a huge investment in observing time of several instruments, and this should be matched by an equally ambitious multi-frequency radio follow-up campaign. As we have experienced, in several of these cases, extreme long integrations produced the very deepest view of the universe in a given waveband. Often, these observations have revealed that source counts in the optical and near-IR are considerably greater that that observed at other wavelengths. What is surprising, however, is that despite this fact, a considerable fraction of the faint radio detections appear to be heavily obscured in the optical (see also Section 11 and 12).

SKA with enormous sensitivity would probe sub-mJy and micro-Jy radio source population, which is believed to be largely associated with massive star formation in distant star forming galaxies. However, a significant fraction of all the sub-mJy sources are also identified with low-luminosity AGN. The remaining, smaller fraction of the faint radio source population are associated with either extremely faint optical identifications, or remain unidentified altogether. We also know that AGN fraction increases rapidly at higher (sub-mJy) flux density limits (Garrett 2002). Therefore, labeling sources as pure "starbursts" or pure "AGN" is a little misleading; it is quite possible (even likely) that both phenomena co-exist in some of these faint systems.

Presently, we are just beginning to appreciate the fact that deep radio observations of a few fields has led us to a sensitivity level where we can expect to detect many discrete radio sources in a single field of view (Garrett 2002). This is quite far from the traditional high-resolution high-frequency, small field of view observations of fields, where very compact, and often very bright radio sources are detected. Several state of the art modes of SKA correlator, *e.g.*, making full use of the raw data i.e to map out the primary beam response of individual resolution elements in their entirety, or simultaneous multiple-field correlation, coupled with incredibly fast data output rates would be key to achieve goals of very high angular resolution imaging of large areas of sky in a single pointing. These radio images would then match the large areas of the sky, which are being routinely surveyed in great detail by optical and near-IR instruments.

12 Deep Imaging of Quasars and Seyfert Galaxies

Our interests lie in studying the radio and optical properties of both quasars and Seyfert galaxies (*e.g.* Wadadekar & Kembhavi 1999, Wadadekar 2004, Singh et al. 2015). Our work so far has been mostly with large area optical and radio surveys.

In addition, we are also interested in deep fields to look for high redshift radio galaxies and radio-loud quasars, which will also be revolutionised by deep fields observed with SKA.

12.1 Deep Imaging of Seyfert Galaxies and the Radio-Loud / Radio-Quiet Divide

Seyfert galaxies have traditionally been categorised as “radio-quiet” AGN. Kellermann et al. (1989) found that the ratio of the radio flux density at 5 GHz to the optical flux density in the B–band was < 10 for radio-quiet AGN. Qualitatively this implied that radio-quiet AGN lacked the kiloparsec-scale jets / outflows that characterised radio-loud AGN. Sensitive radio observations of Seyfert galaxies have however revealed the presence of kiloparsec-scale radio structures (KSRs): Gallimore et al. (2006) detected KSRs in $> 44\%$ of Seyfert galaxies belonging to the complete CfA+12μm sample when observed with the most sensitive D-array configuration of the Very Large Array (VLA) at 5 GHz. Similarly, Singh et al. (2015) found that $> 43\%$ of Seyferts belonging to an eclectic sample derived from the VLA FIRST and NVSS surveys, possessed KSRs. Sensitive multi-resolution, multi-frequency VLA observations have revealed not one set of radio lobes (a.k.a. KSRs) but two of them in the Seyfert galaxy Mrk 6 (Kharb et al. 2006). Radio outflows in Seyfert galaxies are likely episodic. Finally, Ho & Peng (2001) showed that when the optical nuclear luminosity was extracted through high resolution observations (say with the Hubble Space Telescope) and the galactic bulge emission was properly accounted for, then the majority of Seyfert galaxies shifted into the radio-loud class. Kharb et al. (2014) confirmed this trend in the Extended 12μm Seyfert sample, in addition to finding a continuous distribution in the radio-loudness parameters of Seyfert galaxies and low-luminosity FR I radio galaxies. Sensitive imaging of Seyfert galaxies are therefore bridging the radio-loud – radio-quiet divide.

We expect that sensitive observations with the SKA will truly revolutionise this field. Not only will SKA observations probe the full extent of KSRs in Seyfert galaxies and detect steep spectrum radio emission from previous AGN activity episodes if present, it will discover a large number of sources that are “intermediate” between the radio-loud and radio-quiet classes. This will help us understand and better qualify the existence of the dichotomy between AGN having powerful radio outflows and not.

13 Jets in Radio-Quiet AGNs

Using VLBI images of a rigorously selected sample of Seyfert galaxies, we have shown that the radio properties of the compact parsec-scale features are consistent at large the unified scheme for low-luminosity AGNs, with no significant evidence for relativistic beaming. Some detected parsec-scale features in these sources could be termination points of the radio jets (see also Section 12).

The high-resolution, parsec-scale study of low-luminosity analogues of radio-loud AGNs (see also Section 6.2.2) is challenging and this study along with study of a few individual sources is all that we have. This is because, these sources have very low levels of radio flux densities, and hence correlated flux densities of a very few sources meet the sensitivity thresholds currently offered by Global-VLBI. SKA would revolutionize this picture, it would provide us with very high angular resolution at a range of frequencies, thereby enabling us to deduce these conclusions for a statistically significant samples and push these limits further.

14 Polarisation Properties of Radio Jets

We know from the observations of M87 jet that many radio knots are very highly polarized, approaching the theoretical maximum for optically thin synchrotron radiation, suggesting highly ordered magnetic fields. High degrees of polarization are also observed in inter-knot regions. Since, both radio and optical emission from the knots is synchrotron and hence we expect similar radio and optical polarized structures. But, in practice this simple picture is not the case, *e.g.*, even for the brightest, nearby source M87, significant differences have been observed, namely, unlike in the radio, the optical magnetic field position angle becomes perpendicular to the jet at the upstream ends of knots. Moreover, the optical polarization decreases markedly at the position of the flux maxima in these knots. In contrast, the magnetic field position angle observed in the radio remains parallel to the jet in most of these regions, and the decreases in radio polarization are smaller (Perlman et al. 1999).

Presently, forget a statistical picture, we do not even have clear understanding for a handful of low-power FR I radio sources at sub-arcsec scale resolution. Instead, the picture that emerges for jets is therefore rather complex, and it is quite likely that a great many factors could contribute to the general character of a given jet's magnetic field structure. There does appear to be a general correlation between overall "knottiness" and the complexity of polarization structure, and it goes without saying that the most complex structures would be often seen in regions that are either shock-like or associated with apparent bends in the jet. On top, given this complex picture, this understanding cannot be extended to the high-power FR II radio sources, largely due to the dearth of observations. Of course, for a complete understanding of the interaction between the magnetic fields in jets, and the relevant physical parameters over the full range of jet properties, will require an understanding of the jet emission on all scales, across the entire electromagnetic spectrum. SKA would clearly fill some parameter space and provide some insight to the understanding of the polarimetry of the jets of radio galaxies.

15 Gravitational Lensing with SKA

Strong gravitational lensing is the formation of multiple images of a distant background source due to the deflection produced by the gravitational potential of an intervening massive object. Gravitational lenses are a rare occurrence and hence, difficult to find. Large imaging surveys, *e.g.* planned with SKA in the radio, and Euclid and Large Synoptic Survey Telescope (LSST) in the optical, will find over millions of sources out of which over tens of thousands of them will be gravitational lenses.

Efficient lens searches will be key to produce highly complete and pure samples of gravitational lenses. Many lens finding algorithms exist which attempt to automate the process of discovering gravitational lenses. However, most of them fail to reject false positives as efficiently as desired. As a result, visual inspection is still an important step in finding a pure sample of lens candidates for any follow-up investigations. Space Warps, a citizen science project to find lenses combines both approaches and is well suited for a lens search with the SKA. Space Warps uses realistic simulated lenses to track the performance of the citizens and to understand the completeness of the resulting lens sample, which is needed for lens statistics. Since the lensing galaxies are not typically visible in the radio, the synergy between SKA and an optical imaging survey, *e.g.* a complementary optical survey such as the LSST or Euclid will be particularly helpful in the visual identification of the lensing galaxies and the visual confirmation of the lensing nature of these systems. It is noted that the lack of optical imaging and very small image separations will be especially challenging when identifying the lens candidates.

A statistically well-defined sample of lenses can be used to put constraints on cosmological parameters such as the dark energy equation of state (*e.g.*, Chae 2003). The results of Chae

(2003) were obtained from a statistical sample of thirteen radio lenses from the Cosmic Lens All-Sky Survey (CLASS, Browne et al. 2003) whereas with the SKA, we expect to increase the number of lenses by at least two orders of magnitude. The large statistics will greatly improve the existing constraints on cosmological parameters. On the other hand, lens statistics can also be used to probe the average mass density profile of the lens population (*e.g.*, Oguri 2006, More et al. 2012). As pointed out in More et al. (2012), having larger lens samples with well understood selection functions are key to reducing the uncertainties and finding better constraints. Since the SKA will particularly find many small image separation lenses, it would be possible to constrain the mass-luminosity relation by accurately measuring the image separation distribution (Oguri 2006).

Most of the lenses discovered to date have enabled us to probe the mass distribution from galaxy to cluster scales. Since the angular image separations of the lensed sources are a direct indicator of the enclosed lens mass, the study of the lower mass end of the halo mass function is limited by the angular resolution of the telescopes in the radio. Imaging at milli-arcsecond resolution can reveal small-scale deflections produced by lower mass halos referred to as substructure, either luminous (*e.g.*, More et al. 2009, MacLeod et al. 2013) or dark (*e.g.*, Vegetti et al. 2012). Probing the properties of the (dark) substructure is important for testing cosmological predictions of dark matter and strong lensing might be the only technique to enable such study for halos in the distant universe. The SKA will routinely discover extended lensed images at high enough resolution to directly identify several hundreds of candidate lenses with substructure (or sub-halos). With appropriate follow-up, the lens systems will not only put statistically meaningful constraints on the mass function of the sub-halo population but also provide interesting insights in individual cases.

According to the theory of gravitational lensing, faint lensed images very close to the centre of lens are expected to be present but are not usually found in the observations. The properties of these central lensed images, such as the multiplicity and brightness, strongly depend on the density profile *e.g.*, presence of a supermassive black hole (SMBH) at the centre of lensing galaxy can destroy or create additional images with peculiar properties (*e.g.*, Mao et al. 2001). This would be a smoking gun for the detection of a SMBH and would additionally, constrain the mass of SMBHs. The SKA is expected to have the desired combination of both high resolution and high dynamic range to find these faint central images (*e.g.*, Mao & Witt 2012). Needless to say, the SMBH mass estimates from lensing will improve our understanding of the systematic uncertainties on scaling relations, such as the BH mass - galaxy velocity dispersion relation derived from other techniques like reverberation mapping and extend our knowledge in redshift and SMBH mass to a regime where kinematic measurements are not possible.

16 Surprises: Serendipitous Discoveries, Discovery of New Objects, Technology Development, etc.

This is the fitting place to end this document! Along with some of us, who have contributed to this document, we are sure, many others too would be excited and would like to be part of any discovery, *e.g.*,

(i) cosmic Microwave Background radiation by Penzias and Wilson (1965),

(ii) Quasars and radio galaxies as cosmological probes (3C radio source catalogue), the weaker sources of smaller flux densities had smaller angular size, compared to angular size of stronger 3C sources with higher flux densities, this showed the cosmic evolution of these objects;

(iii) or the violent phenomenon occurring in the cores of quasars and radio galaxies, indicating the presence of supermassive black holes.

(iv) Fanaroff-Riley class I and class II radio galaxies (Fanaroff & Riley 1974).

(v) Or alternatively, the techniques: Radio interferometry (Ryle 1962), self-calibration (Cornwell 1989),

(vi) or the search for extra-terrestrial intelligence.

And of course, many other exotic object(s) to which superlatives, like 'new class', 'unusual', 'super-', 'most', 'farthest', 'nearest' 'biggest', 'smallest', 'brightest', 'calmest', 'heaviest', 'lightest', etc. could be associated.

Acknowledgments

We thank all the members of the astronomy and astrophysics community of India stationed across several parts of the world. We also thank Dr. Tirthankar Roy Choudhury for sending us timely reminders and his constant push, otherwise we would not have been able to bring this document to this state. The work of the SKA Organisation is overseen by its Board of Directors. Presently, Prof. Yashwant Gupta from the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research is one of the SKA board member. India is one of the 11 member countries forming the core of the SKA. We thank the staff of the GMRT that made these observations possible. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy. upport for the MWA comes from the U.S. National Science Foundation, the Australian Research Council, the U.S. Air Force Office of Scientic Research, and the Centre for All-sky Astrophysics. Support is also provided by the Smithsonian Astrophysical Observatory, the MIT School of Science, the Raman Research Institute, the Australian National University, and the Victoria University of Wellington. Additional research support is provided by Swinburne University of Technology, the University of Sydney, University of Tasmania and University of Washington.

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Solar, Heliospheric and Ionospheric Science with Square Kilometer Array and its Precursors

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1 Introduction

Historically, the progress in astrophysics has been closely related to the march of technology. For the next few decades, the Square Kilometre Array (SKA) will be the confluence of many new technologies brought together for the benefit of radio astrophysics. Spanning the frequency range from few 10s of MHz to a few GHz, the SKA is being designed to exceed the performance of the present generation instruments by at least an order of magnitude in most respects. The SKA will open up vast new volumes in the exploration phase space, extending it simultaneously along dimensions of sensitivity, angular resolution, access to large bandwidths, imaging fidelity, and perhaps time and frequency resolution of its images. These new capabilities will allow us to address a broad range of hitherto inaccessible science.

In the history of solar physics, every telescope which extended the observing phase space in a significant manner discovered something new and interesting, and often unexpected as well. This can justifiably be expected to be true for the SKA as well. In addition to solar physics, in this article we have also included heliospheric and ionospheric science, as they all form parts of Space Weather science and from a Sun–Earth system perspective, they are best treated as a tightly coupled system. To guide the process of doing science in a large international collaboration, SKA Science Working Groups (SWGs) for various areas of astrophysics were set up. These groups had laid down performance parameters which needed to be met by the instrument design and have also been updating the science case. As of now, there is no SWG for Solar, Heliospheric and Ionospheric (SHI) science. This is both an opportunity and a challenge. The challenge comes from the fact with no advocacy from a SWG till this late stage, in all likelihood we have lost the opportunity to influence the instrument design to better serve the needs of SHI science. Our opportunity stems from the fact that by building a coherent community to pursue SHI science, we can place ourselves in a position of advantage to pursue SHI science with the SKA. How the SKA will allocate observing time and data rights is yet to be decided, it is fair to expect that the formation and membership of a SKA SHI SWG will only help.

This article is an compilation of some of the interesting SHI science which SKA can be expected to do. It is incomplete, reflects my biases and draws heavily on the recently published SKA solar and heliospheric science case Nakariakov et al. (2015).

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2 Solar Science

Though the Sun is the brightest radio source visible from the Earth, it is also a very challenging source to study in detail. The characteristics of solar emissions include temporal variability on scales from milli-seconds to solar cycles, spectral variability on scales down to 100s of kHz, emission morphology changing on sub-sec time scales, emissions at sizes expected to as small as 10s of meters for magnetic reconnection to angular sizes of about a degree for synchrotron emission from Coronal Mass Ejection (CME) plasma, and emissions mechanisms differing in strengths by 7–8 orders of magnitude. Detailed observations of a source like this require high fidelity spectroscopic imaging capability with a high time and angular resolution over a wide bandwidth. Though the new generation instruments like the Murchison Widefield Array (MWA) and LOw Frequency ARray (LOFAR) are a big step forward, they are limited to metrewave bands and below and the SKA will far exceed their capabilities.

We list below some of the key solar science areas where the SKA is expected to make a dominant contribution:

1. ***Magnetic Reconnection Diagnostics*** – It is now widely believed that flares represent the release of energy stored in magnetic fields by the process of magnetic reconnection. Many unsolved problems about the physical processes involved, however, still remain. The key piece of information needed for addressing these questions is the magnetic field configuration. The magnetic fields cannot be measured directly and are ususally inferred using force-free extrapolations from the fields measured at the photosphere. However the non force-free nature of lower layers of solar atmosphere make this approach problematic. The gyrosynchrotron emission from energetic electrons in flaring loops, which dominates the emission at a few GHz, provides a robust technique to constraint the coronal magnetic fields. The high fidelity spectroscopic imaging capability of the SKA over a wide band extending to a few GHz is ideally suited for this application.

   Another aspect where the SKA will help make progress is about the sites of magnetic field reconnection. Though the reconnection sites cannot themselves be observed directly, understanding the energy release process requires the information of locations and spatial extents of these sites. Non-thermal particles produced during the flare events allow radio observations to indirectly image the reconnection site. The improved spatial resolution from the SKA will help gather this information and constrain the theoretical models.

2. ***Quasi-periodic pulsations in flares*** – The light curves of solar (and stellar) flares are sometimes found to have pronounced quasi periodic pulsations (QPPs). They are seen in wavebands ranging from radio to X-ray and gamma-ray, with periods ranging from fractions of a second to tens of minutes and modulations from a few percent to a hundred percent. Theoretical studies suggest that such periodicities might be caused by MHD oscillations in the flaring region or nearby plasma structures. An unambiguous identification of MHD osciallations in the flares which QPPs requires a combination of high spatial and temporal resolution with high sensitivity and large spectral coverage, all attributes of the SKA. Progress in understanding of QPPs can potentially provide a tool for MHD seisemology and have applications in building an improved understanding of other flare stars.

3. ***Shocks and particle acceleration in the corona*** – CMEs often drive shocks in the solar atmosphere and these shocks form the sites for electron acceleration. The acceleration mechanisms are believed to include magnetic reconnection and coronal shock waves, though the precise details of these processes remain unclear. The high resolution and

imaging dynamic range SKA observations can not only give us new insights into the physics of CMEs and associated shocks but also help improve space weather forecasts. It is worth noting that the theoretical modeling of type II bursts often associated with CMEs and type III bursts associated with electron beams believed to be accelerated at isolated magnetic reconnection sites are an active area of research and are being increasingly successful in using force-free 3-D MHD simulations seeded with data driven models to match the observed dynamic spectra.

4. ***Radio signatures of nano-flares and the coronal heating problem*** – Nano-flares were hypothesised by Parker in 1960s as a possible solution to the coronal heating problem. He envisaged a scenario with a large number of weak events producing a statistically steady background providing the heat flux to the corona. The individuals events are expected to be too faint to observe by the current generation instruments. These nano-flares are believed to be small magnetic reconnection events, and should have radio counterparts associated with them. The dominant emission process is expected to be the plasma emission, which gives rise to coherent radiation at the local plasma frequency and its harmonic. The coherent nature of this radiation leads to a large observational signature even for intrinsically low energy events, making radio band the most promising one to look for signatures of these nano-flares. Recent work with the MWA shows evidence of presence of weak non-thermal emission features with rates $\sim$1000 events/hr in a bandwidth of $\sim$30 MHz, even during quiet sun periods. Sensitive SKA-Low observations over large bandwidths will allow us to better characterise these events and look for even weaker population of non-thermal emissions, hopefully contributing to a resolution of the long standing coronal heating problem.

5. ***Propagation effects in the corona*** – Recent MWA observations of a type II burst have revealed interesting details which imply that propagation effects must play an important role in the corona. While this is hardly a surprise and has long been expected, the spectroscopic imaging with sufficient time and frequency resolution to study this in detail is becoming available only now. Wider bandwidth observations with higher angular resolution are needed to constrain effects of scatter broadening, ducting, and directivity of coherent emission processes, which in turn will constrain the nature of coronal turbulence and density inhomogeneities and also elucidate some aspects of the emission process itself.

3 Heliospheric Science

Our modern suite of instruments provides a pan-chromatic near 24/7 view of the Sun. However the solar wind, which carries the influence of the Sun to the Earth and gives rise to Space Weather events, becomes much harder to study directly once it goes beyond the FOVs of the chronographs. For a long time, our next opportunity to study the solar wind came only when it arrived at the near Earth satellite based observatories. The situation improved with the availability of heliospheric imagers like STEREO, and Solar Mass Ejection Imager before it (2003-2011), which can image structures with large scale density enhancements in solar wind using the Thomson scattered light from the electrons.

Radio observations in the metrewave range provides some very useful remote sensing techniques to study the heliosphere, namely Inter-Planetary Scintillation (IPS) and Faraday rotation. As with all propagation effects, the measurables for both these techniques are integrals along the line-of-sight (LoS).

3.1 Interplanetary Scintillation

IPS is the radio analogue of optical twinkling of stars. As the plane wavefront from a compact distant radio source passes through the solar wind, the variations in density along the LoS give rise to fluctuations in refractive index of the medium, which leads to development of corrugations in the wavefront. By the time this corrugated wavefront arrives at the Earth based telescope, the phase fluctuations develop into intensity fluctuations. As this interference pattern streams past the telescope, due to the motion of the solar wind, the gives rise to IPS.

Since its discovery in mid 60s, IPS has been used extensively to characterise the large scale structure of the solar wind in the vast interplanetary medium. Many of the key discoveries made using IPS observations were confirmed later by satellite based observatories. Despite its long history, IPS continues to remain a very competitive tool for heliospheric research and space weather applications. Its primary advantages come from:

1. its unique ability to measure the fluctuations in the electron density (δn_e) and the slope of its power spectrum (k), and the velocity of the solar wind (v).

2. its ability to sample the entire inner heliosphere.

The time and length scales associated with micro-turbulence are too small to be observed by current and upcoming instrumentation. While it is possible for *in-situ* instruments to measure it locally, IPS is the only known remote sensing technique to measure it over a large volume of the heliosphere. This ability of IPS allows it to track the evolution of large scale structures in the solar wind like CMEs and Corotating Interaction Regions (CIRs), as well as smaller scale features.

We list below some of the different studies expected to yield interesting new science with the SKA:

1. Simultaneous observations over a large range of frequencies to examine the scale size of density irregularities, and studying the transition from weak to strong scattering.

2. Investigations of turbulence scale and spectrum of the solar wind.

3. Observations of IPS dynamic spectra to understand its the spectral coherence lengths.

4. Well planned extensive multi-site IPS observing campaigns to build 3D models of distribution of electron density, fluctuations in electron density and velocity.

Similar lines of research are being pursued with other new generation instruments like LOFAR (Fallows et al. 2013), and have been planned with the MWA (Oberoi & Benkevitch 2010).

3.2 Faraday Rotation

The key requirement from space weather forecasts is to reliably predict the geo-effectiveness of CMEs. Due its large socioeconomic impact, it has repeatedly been identified as a high priority objective. The long standing impediment to achieving this has been the inability to measure the orientation of the magnetic fields in the CMEs. For the current technology it is only possible to measure it using *in-situ* satellite based instrumentation. However, by the time this is measured at our outermost sentry, locate at the L1 point, it leaves us with a response time of a few tens of minutes, too short to take effective remedial measures.

Faraday rotation of the plane of polarisation of linearly polarised background sources has been suggested as a possible technique to measure magnitude and orientation of CME magnetic fields. This technique was pioneered using telemetry signals from spacecraft (Levy et al. 1969), and has continued to remain a productive approach (Jensen et al. 2013). It has been demonstrated on astronomical sources under favourable conditions (Ingleby et al. 2007; Kooi et al. 2014), and forms a part of the science case of the new generation instruments like the MWA (Oberoi & Benkevitch 2010).

Though active research is being pursued to realise the potential of this technique, its efficacy at predicting the CME magnetic field strength and topology is yet to be observationally verified. The low level signature of CME magnetic field, implies that these observations are best done at metrewave bands or longer wavelengths. On the other hand, the fractional polarisation of most extra-galactic linearly polarised sources drops, the ionospheric contamination to Faraday rotation increases, and the Galactic background becomes brighter at these frequencies. The reduction in polarised flux of extra-galactic source is more than compensated by the appearance of linearly polarised patches in the diffuse Galactic background, though these structures have strong frequency dependence and require more effort to deal with. The heliospheric Faraday rotation signature is expected to rapidly drop to $\sim$10% of that the ionospheric Faraday rotation, as the CME moves away from the Sun, Hence, to use these observations as a reliable space weather forecasting tool will require calibration of ionospheric Faraday rotation to a few % level. The very high sensitivity, high quality instantaneous point-spread-function, and the large FoV of the SKA-1 low frequency instrument, make it the most promising tool yet for pursuing this approach.

4 Ionospheric Science

In much of radio astronomy, ionospheric effects are regarded as a contamination which one needs to get rid off to get to the true astronomical signal. However, for sensitive, large FoV instruments like the SKA-Low, this also provides an excellent opportunity to pursue novel ionospheric science. Ironically, interferometers are more sensitive probes of some aspects of the ionosphere than many of the instruments dedicated for ionospheric research. This sensitivity comes from the fact that the interferometers measure the differential phase between the radiation arriving at the two antennas forming a baseline. This differential phase encodes the information of the structure and location of the source. The LoS from the different antennas pass through different paths through the ionosphere, the differences in propagation effects arising from the differences in the electron density and magnetic field distributions between these LoS contribute an additional phase to the measured cross-correlation. In fact, for antennas with wide FOVs, the LoS from a given antenna towards different directions traverse different paths through the ionosphere as well. The process of ionospheric calibration, which relies on measuring the phases towards a large number of sources of known structure and flux, referred to as calibrators, tries to separate this phase from the astronomical phase. These calibration solutions contain detailed time dependent information about ionospheric inhomogeneities on the length scales of baselines towards the directions of calibrator sources over a patch the size of the FOV of the telescope. This provides a dataset with unprecedented ability to do a detailed characterisation of the ionospheric inhomogeneities on length scales much finer than usually probed by ionospheric instruments and enable novel investigations probing hitherto inaccessible aspects of ionospheric physics. This promise is already being realised by MWA which has provided the first direct evidence for large scale cylindrical electron density structres aligned with the local geomagnetic field bridging upper ionosphere and inner plasmasphere (Loi, private communication, 2015). It will be a lost opportunity if the SKA data products are not used to pursue the ionospheric science it will enable.

5 Operating Mode

Practically all conventional solar and heliospheric research instruments monitor the Sun and heliosphere, respectively, for the longest duration possible every day. The SKA cannot be expected to be operated routinely in such a monitoring mode. A more feasible approach to using the SKA for SHI science will be to use it for SHI science in a campaign mode, perhaps along the lines of the *Whole Sun Month* campaigns which were mounted in the 1990s and 2000s.

6 Conclusions

The SKA science will be rich and interesting, but the volume of work will be large. It will require a coherent and inclusive team of scientists striving for this shared goal, and a well planned systematic approach to laying the ground work for enabling it, on both scientific and organisational fronts. The work will range from preliminary studies to sharpen the science questions, to planning the details of analysis and training a generation of students to accomplish this science. This article only scratches the surface of possible SKA SHI science, and not surprisingly, reflect my biases. The absence of an international SKA–SWG for SHI science does present an opportunity to interested Indian scientists. We invite you to consider how the science which you are interested in pursuing might benefit from the SKA, contemplate novel SHI science, enabled by the SKA, of particular interest to you, and contribute to the SKA SHI WG. We hope that this document will seed the effort of realising this opportunity and a vibrant and concerted effort to pursue SHI science with the SKA.

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