Review

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Neutron Star Physics in the Square Kilometre Array Era: An Indian Perspective

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Abstract. It is an exceptionally opportune time for astrophysics when a number of next-generation mega-instruments are poised to observe the Universe across the entire electromagnetic spectrum with unprecedented data quality. The Square Kilometre Array (SKA) is undoubtedly one of the major components of this scenario. In particular, the SKA is expected to discover tens of thousands of new neutron stars giving a major fillip to a wide range of scientific investigations. India has a sizeable community of scientists working on different aspects of neutron star physics with immediate access to both the uGMRT (an SKA pathfinder) and the recently launched X-ray observatory Astrosat. The current interests of the community largely centre around studies of (a) the generation of neutron stars and the SNe connection, (b) the neutron star population and evolutionary pathways, (c) the evolution of neutron stars in binaries and the magnetic fields, (d) the neutron star equation of state, (e) the radio pulsar emission mechanism, and (f) the radio pulsars as probes of gravitational physics.

Most of these studies are the main goals of the SKA first phase, which is likely to be operational in the next four years. This article summarizes the science goals of the Indian neutron star community in the SKA era, with significant focus on coordinated efforts among the SKA and other existing/upcoming instruments.

Key words. Neutron stars: generation, population, EoS, magnetic fields—radio pulsar: emission—radio pulsars: gravitational waves.

1. Introduction

Since the first detection of a neutron star (NS) 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. 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 importance. Potential applications include pulsar search and survey, high precision pulsar timing to test gravity theories as well as detect gravity waves, pulsar magnetospheric studies, characterization of transient objects (like rotating radio transients or 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, availability of large number of simultaneous beams in the sky 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). Here, we focus on the areas of particular interest to the Indian scientists working in different areas of neutron star physics in the SKA context.

2. The generation: NS–SNR associations

Canonically neutron stars are created as end products of core collapse supernovae (CC-SNe). To date, only 79 of them have been spatially associated with supernovae remnants (SNR). While in most cases, the spin down ages of the pulsars match well with the life time of the SNRs, there exist several objects of comparable age, for which no SNRs have been detected in any electromagnetic band. This could be a selection effect, caused by the sensitivity limitations of the (multi-waveband) instruments, or it could be due to factors controlling the temporal and spatial evolution and emissivity of the SNRs. As the supernova shock propagates through the interstellar medium (ISM), forming an SNR, its lifetime is dominated by the following four distinct phases.

(1) *The free expansion phase*: This may last for several hundred years and is dominated by thermal emission, wherein the mass of the swept up ISM dust and gases is very small compared to the mass of the ejecta ($M_{\rm ISM} \ll M_{\rm ejecta}$), with the temperature of the fast moving medium being in the range $T \sim 10^6$–10^7 K (Chevalier 1977).
(2) *The adiabatic* (*Sedov–Taylor*) *expansion phase*: This is reached when $M_{\rm ISM} \simeq M_{\rm ejecta}$, and in this phase the cooling ejecta also emits X-ray lines and thermal bremsstrahlung in the entire electromagnetic band from the radio to the X-rays.
(3) *The 'snow-plough' phase*: This is dominated by radiative cooling, and is reached when $M_{\rm ISM} \gg M_{\rm ejecta}$, and $T \leq 10^5$ K, leading to optical and UV line emission. This phase continues for $\sim 10^5$ yr.
(4) The final mixing of the ISM and the ejecta such that the shell breaks up in clumps (possibly due to Rayleigh–Taylor and Kelvin–Helmholtz instabilities) and disperses the SN-provender's material, and the energy of the shock is dissipated in the ISM.

The duration for which the SNR remains in each phase, and its spectra, are determined by the strength of SNe shock, the $M_{\rm ejecta}$, the density of the ISM (all of which in turn depend on the properties of the progenitor), and also on the mass and thermodynamic properties of the ISM.

In the absence of a central compact object (CCO), SNRs are mostly identified by their morphology (shell-like, plerionic, or composite structure) and the presence of non-thermal (synchrotron) emission, emitted mainly by highly relativistic electrons accelerated by magnetic fields trapped in the remnant, along with some diffuse emission from thermal bremsstrahlung processes. While the reverse shock in a young SNR serves as a good accelerator, in older SNRs, the radio morphology (mainly filamentary emission) and luminosity also trace out regions of turbulence induced amplification of magnetic fields in the SNRs, caused by interaction with the ISM clouds. Further, the spectral index of the synchrotron emission (especially early in the lifetime of the SNR), can be changed significantly by the high energy cosmic rays (mainly protons) in the presence of strong magnetic fields (Jun & Jones 1999).

There exist several radio pulsars (PSR) with spin down ages below $\tau \simeq 10^4$ yr, with magnetic field in the range of $10^{12} < B_{\rm surf} \simeq 10^{14}$ G (i.e. from 'ordinary' pulsars to magnetars), which have no observational evidence of any associated SNRs (see Table 1). Likewise, while the presence of a CCO would confirm a CC-SNe, its absence in an SNR may also be because of a high kick velocity imparted to the CCO at birth, or because the emission is beamed away from us, with any thermal radiation being below the detection threshold of instruments in appropriate wavebands (young CCOs emit thermally in the 0.2–10 keV band). For example, the nearest, recent SNR, SN1987A, shows no CCO but Very Large Array (VLA) observations do show some evidence of a pulsar wind nebular (PWN). Finally, the paucity of SNR–PSR associations may simply be because (a) the canonical 'age' of SNRs is being grossly over-estimated, and/or (b) the pulsar velocities at birth may have been severely under-estimated. These raise important questions about galactic rate of all types of supernovae, the poorly understood physics of supernovae and neutron star (or magnetar) formation, and SNe shock–ISM interaction. The high spatial resolution

Table 1. Pulsars with no associated SNRs.

	Name	Association	τ_s (Yr)	B_{surf} (G)	$\dot{E}_{rot}$ (erg.s^{-1})
1	J1050−5953	XRS	2.68e+03	5.02e+14	5.6e+33
2	J1023−5746	GRS(F)	4.6e+03	6.62e+12	1.1e+37
3	J1838−0537	*	4.89e+03	8.39e+12	6.0e+36
4	J0100−7211	EXGAL:SMC,XRS	6.76e+03	3.93e+14	1.4e+33
5	J1357−6429	XRS:PWN	7.31e+03	7.83e+12	3.1e+36
6	B1610−50	*	7.42e+03	1.08e+13	1.6e+36
7	J1617−5055	GRS	8.13e+03	3.1e+12	1.6e+37
8	J1734−3333	*	8.13e+03	5.22e+13	5.6e+34
9	J1708−4008	XRS	8.9e+03	4.7e+14	5.8e+32
10	J1418−6058	GRS(F),GRS(H)	1.03e+04	4.38e+12	4.9e+36
11	J1301−6305	*	1.1e+04	7.1e+12	1.7e+36
12	J1809−1943	XRS(AXP)	1.13e+04	2.1e+14	1.8e+33
13	J1746−2850	*	1.27e+04	3.85e+13	4.2e+34
14	J1420−6048	GRS(F),GRS(H)	1.3e+04	2.41e+12	1.0e+37
15	J1413−6141	*	1.36e+04	9.88e+12	5.6e+35
16	J1826−1256	GRS(F),XRS(AXP),PWN	1.44e+04	3.7e+12	3.6e+36
17	J1702−4310	*	1.7e+04	7.42e+12	6.3e+35
18	J2021+3651	GRS,GRS(F)	1.72e+04	3.19e+12	3.4e+36
19	J2111+4606	GRS(F)	1.75e+04	4.81e+12	1.4e+36
20	J2004+3429	*	1.85e+04	7.14e+12	5.8e+35
21	B1046−58	GRS(F)	2.03e+04	3.49e+12	2.0e+36
22	B1737−30	*	2.06e+04	1.7e+13	8.2e+34
23	J1856+0245	GRS(H),XRS (AXP)	2.06e+04	2.27e+12	4.6e+36
24	J1935+2025	*	2.09e+04	2.23e+12	4.7e+36
25	B1823−13	GRS,XRS:PWN	2.14e+04	2.8e+12	2.8e+36
26	J1934+2352	*	2.16e+04	4.89e+12	9.1e+35
27	J1958+2846	GRS(F)	2.17e+04	7.94e+12	3.4e+35
28	J1838−0655	XRS (AXP), GRS(H)	2.27e+04	1.89e+12	5.5e+36
29	J1135−6055	*	2.3e+04	3.05e+12	2.1e+36
30	J1909+0749	*	2.47e+04	6.07e+12	4.5e+35
31	J1410−6132	*	2.48e+04	1.28e+12	1.0e+37
32	J1747−2958	GRS (PWN)	2.55e+04	2.49e+12	2.5e+36
33	B1727−33	*	2.6e+04	3.48e+12	1.2e+36
34	J2238+5903	GRS(F)	2.66e+04	4.02e+12	8.9e+35
35	J1821−1419	*	2.93e+04	3.89e+13	7.8e+33
36	J1841−0524	*	3.02e+04	1.03e+13	1.0e+35
37	J1524−5625	*	3.18e+04	1.77e+12	3.2e+36
38	J1112−6103	*	3.27e+04	1.45e+12	4.5e+36
39	J1718−3718	*	3.32e+04	7.47e+13	1.7e+33
40	J1837−0604	*	3.38e+04	2.11e+12	2.0e+36
41	J1833−0831	XRS (SGR)	3.49e+04	1.63e+14	3.1e+32
42	J0729−1448	*	3.52e+04	5.4e+12	2.8e+35
43	J1932+1916	*	3.54e+04	4.46e+12	4.1e+35
44	J1551−5310	*	3.68e+04	9.52e+12	8.3e+34
45	J1907+0918	*	3.8e+04	4.67e+12	3.2e+35
46	J1015−5719	*	3.86e+04	2.87e+12	8.3e+35
47	B1930+22	*	3.98e+04	2.92e+12	7.5e+35
48	J1044−5737	GRS(F)	4.03e+04	2.79e+12	8.0e+35
49	J1815−1738	*	4.04e+04	3.98e+12	3.9e+35
50	J1637−4642	*	4.12e+04	3.06e+12	6.4e+35
51	J1849−0001	XRS,GRS,GRS(H)	4.29e+04	7.49e+11	9.8e+36
52	J1745−2900	XRS (AXP)	4.31e+04	7.3e+13	1.0e+33
53	J1813−1246	GRS	4.34e+04	9.3e+11	6.2e+36
54	J0631+1036	GRS(F)	4.36e+04	5.55e+12	1.7e+35
55	J0940−5428	*	4.22e+04	1.72e+12	1.9e+36
56	J0631+1036	GRS(F)	4.36e+04	5.55e+12	1.7e+35

Table 1. (*Continued*).

	Name	Association	τ_s (Yr)	B_{surf} (G)	$\dot{E}_{rot}$ (erg.s^{-1})
57	J1524−5706	*	4.96e+04	2.02e+13	1.0e+34
58	J1412−6145	*	5.06e+04	5.64e+12	1.2e+35
59	J1809−1917	XRS (PWN)	5.13e+04	1.47e+12	1.8e+36
60	J1737−3137	*	5.14e+04	e+12	6.0e+34
61	J1838−0453	*	5.22e+04	6.72e+12	8.3e+34
62	J1055−6028	GRS	5.35e+04	1.74e+12	1.2e+36
63	J1702−4128	*	5.51e+04	3.12e+12	3.4e+35
64	J1422−6138	*	5.58e+04	5.81e+12	9.6e+34
65	J1841−0345	*	5.59e+04	3.48e+12	2.7e+35
67	J0633+0632	GRS(F)	5.92e+04	4.92e+12	1.2e+35
68	J1429−5911	GRS(F)	6.02e+04	1.9e+12	7.7e+35
69	J1406−6121	*	6.17e+04	3.45e+12	2.2e+35
70	J1938+2213	*	6.2e+04	2.69e+12	3.7e+35
71	J0248+6021	GRS(F)	6.24e+04	3.5e+12	2.1e+35
72	J1541−5535	*	6.25e+04	4.77e+12	1.1e+35
73	J1413−6205	GRS(F)	6.28e+04	1.76e+12	8.3e+35
74	J1806−2125	*	6.29e+04	7.74e+12	4.3e+34
75	J1105−6107	XRS	6.33e+04	1.01e+12	2.5e+36
76	J1459−6053	GRS(F)	6.47e+04	1.63e+12	9.1e+35
77	J1850−0026	*	6.75e+04	2.58e+12	3.3e+35
78	J0534−6703	EXGAL:LMC	6.78e+04	2.81e+13	2.8e+33
79	J0146+6145	XRS	6.91e+04	1.33e+14	1.2e+32
80	J1954+2836	GRS(F)	6.94e+04	1.42e+12	1.0e+36
81	J1636−4440	*	7.01e+04	3.14e+12	2.1e+35
82	J1857+0143	*	7.1e+04	2.11e+12	4.5e+35
83	J1601−5335	*	7.33e+04	4.29e+12	1.0e+35
84	J1828−1101	*	7.71e+04	1.05e+12	1.6e+36
85	J0901−4624	*	8e+04	6.29e+12	4.0e+34
86	B1727−47	*	8.04e+04	1.18e+13	1.1e+34
87	J1855+0527	*	8.26e+04	1.95e+13	3.9e+33
88	J1928+1746	*	8.26e+04	9.64e+11	1.6e+36
89	J1847−0130	*	8.33e+04	9.36e+13	1.7e+32
90	J1705−3950	*	8.34e+04	4.45e+12	7.4e+34
91	J1814−1744	*	8.46e+04	5.51e+13	4.7e+32
92	J1738−2955	*	8.58e+04	6.1e+12	3.7e+34
93	J1638−4608	*	8.56e+04	3.83e+12	9.4e+34
94	J1803−2149	GRS(F)	8.63e+04	1.46e+12	6.4e+35
95	B1916+14	*	8.81e+04	1.6e+13	5.1e+33
96	B0611+22	*	8.93e+04	4.52e+12	6.2e+34
97	J1718−3825	GRS(F),GRS(H)	8.95e+04	1.01e+12	1.3e+36
98	J1028−5819	GRS(F)	9e+04	1.23e+12	8.3e+35
99	J1913+0446	*	9.18e+04	2.15e+13	2.6e+33
100	J1558−5756	*	9.54e+04	1.46e+13	5.2e+33
101	J1531−5610	*	9.71e+04	1.09e+12	9.1e+35
102	J1909+0912	*	9.87e+04	2.86e+12	1.3e+35
103	J2216+5759	*	9.62e+04	5.44e+12	3.7e+34

*List of all pulsars with spin down ages $<10^5$ yr, with no associated supernova remnant. The list is in ascending order of age, and the surface magnetic field (B_{surf}), and rotational energy ($\dot{E}_{rot}$) of the pulsar are provided. Extra-galactic sources, those associated with pulsar wind nebulae (PWN), magnetars (SGRs or AXPs) or any other spatially coincident X-ray source (XRS), or gamma-ray source (GRS) discovered by Fermi (F) or Hess (H) is indicated. For further details of pulsar properties, associations and references, please see the ATNF pulsar catalogue.

of SKA, and its higher sensitivity should be able to answer at least some of these, both by probing the structure of Galactic SNRs down to higher resolution and faintness, and by discovering new SNRs which may have been missed out due to limits on the current surveys.

The neutron stars associated with the CC-SNe fall into two categories: the pulsar wind nebula and the central compact objects. In young pulsars, the rapid rotation and large magnetic fields ($B \geq 10^{12}$ G) accelerate particles and produce energetic winds, resulting in spin-down of the neutron star. Confinement of the pulsar winds in the surrounding medium generates luminous PWN seen all across the electromagnetic spectrum, shining most prominently in radio and X-rays. First proposed by Rees & Gunn (1974), morphology of the PWN can provide crucial information on the properties of the outflow, the interacting ambient medium and the geometry of the pulsar powering it (see Gaensler & Slane 2006 and references therein). In the innermost regions, relativistic outflows in the form of torus and jets are formed; the geometry of which reveals the orientation of the pulsar spin axes and can provide information on the formation of kicks imparted in the moments following their formation. The larger-scale structures of the PWN provide insights on the ambient magnetic field and signatures of interaction with the supernova ejecta. The evolution of a PWN inside an SNR follows three important evolutionary phases: an initial free-expansion in the supernova ejecta, the collision between the PWN and SNR reverse shock, which crushes the PWN subjecting it to various instabilities, and eventually subsonic re-expansion of the PWN in the shock heated ejecta (Gelfand *et al.* 2007 and references therein). An additional later phase might also be identified, when the pulsar's motion becomes supersonic as it approaches the shell of the supernova remnant and it acquires a bow-shock morphology (van der Swaluw *et al.* 2004).

CCOs are X-ray point-like sources found at the centre of supernova remnants (Pavlov 2005). They have a purely thermal X-ray spectrum with $KT \sim 0.2$–0.5 keV and luminosity $\sim 10^{33} - 10^{34}$ erg s^{-1}. No radio/gamma-ray counterparts have been found. There is also no evidence of an extended nebular emission surrounding these objects.

The higher sensitivity and spatial resolution of the SKA would allow simultaneous imaging of SNR/PWN, along-with time series observations of any plausible associated pulsar candidate. For example, the primary beam at Band-2 of the proposed SKA-mid is $\sim 50'$, which is larger than the apparent size of most of the known SNRs (Green 2014). At the same time, with the longest baseline of about 160 km, high dynamic range images (which are not confusion limited) of these sources can be obtained with a resolution better than a third of an arc-second. Deep, high resolution images obtained with the SKA are therefore likely to (a) discover faint emission from the SNRs and (b) increase the number of pulsar-PWN associations. Coupled with simultaneous sensitive time resolution searches with the SKA, these can be very useful in constraining evolution and dynamics of such objects (Castelletti *et al.* 2011, 2013; Supan *et al.* 2015).

3. The population

3.1 *Classification*

Even though some 2500 neutron stars with diverse characteristic properties have been observed, 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).

(1) *Rotation powered pulsars* (*RPP*): As of now, there are about three types that fall into these categories.
   (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) subclass 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 $B_\mathrm{p} < 10^{11}$ 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.
(2) *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 $B_\mathrm{p} \sim 10^{12}$ G and *O* or *B* type companions and mostly show up as X-ray pulsars (XRP) (Caballero & Wilms 2012). They have a hard X-ray spectrum (KT > 15 keV). The spectrum exhibits possible signatures of interaction of the accreted material with the strong magnetic field of the neutron star in the form of Comptonization, and the presence of broad absorption lines known as Cyclotron Resonance Scattering Features (CRSF). CRSFs are found in more than 20 XRPs, and is a direct tracer of the magnetic field strength of the neutron star from the 12-*B*-12 rule: $E_\mathrm{c} = 11.6$ keV $\times \frac{1}{1+Z} \times \frac{B}{10^{12}}$ G; E_c being the centroid energy, z the gravitational redshift and B the magnetic field strength of the neutron star.
   (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).
(3) *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 (CCO) are characterized by the absence of both associated nebulae and 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 & Arjunwadkar 2016). 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 *et al.* 2009; Kaspi 2010; Viganò 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.

3.2 *Radio pulsars: Statistical studies*

Timing irregularities seen in radio pulsar rotation rates are of two kinds: (a) timing noise: continuous, noise-like fluctuations and (b) glitches. The abrupt cessation of pulsed radio emission for several pulse periods, observed in some hundred odd pulsars, is known as the phenomenon of nulling. The nature and degree of this nulling varies from one pulsar to the other. We undertake a comprehensive statistical study of these pulsars and also include the intermittent pulsars and the RRATs in our study. Recently, it has been suggested that there may exist a trend for nulling activity, going from ordinary nulling pulsars to intermittent pulsars to RRATs. Here we try to quantify the nulling behaviour to check for any difference between these different classes of pulsars. With that aim we find the proximity of a given object to the death-line. We

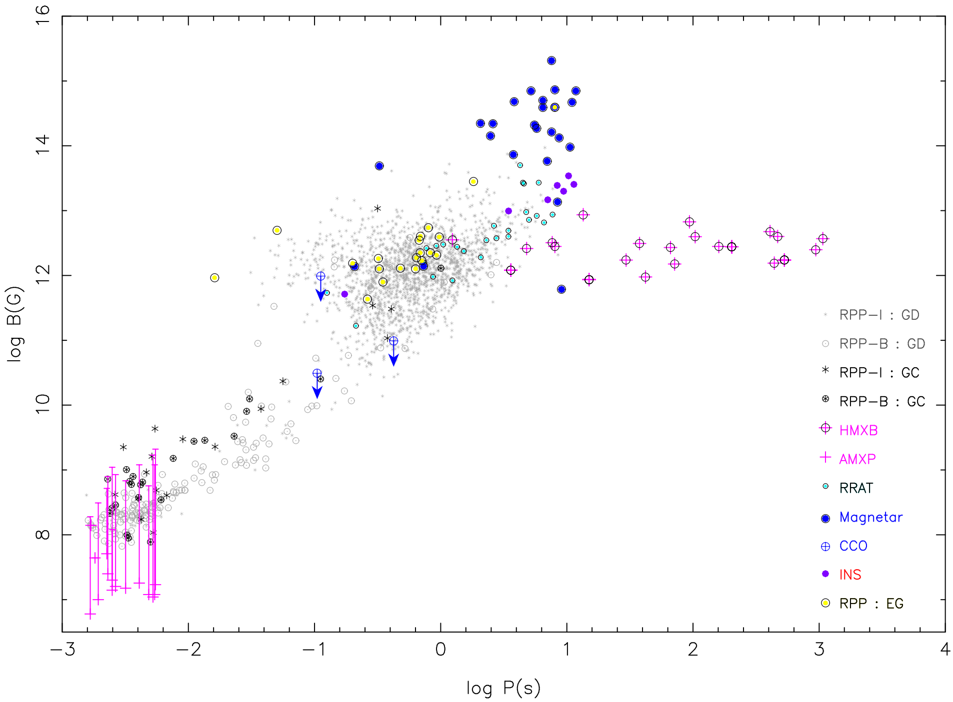

Figure 1. The menagerie: Different observational classes of neutron stars shown in the spin-period vs. surface magnetic field ($P_s - B_s$) plane. Legends: I/B - isolated/binary, GC – globular cluster, GD – galactic disc, EG – extra-galactic objects Data: RPP – ATNF pulsar catalogue, RRAT – http://astro.phys.wvu.edu/rratalog/, 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 Kerkwijk (2009); CCO – Halpern & Gotthelf (2010), Ho (2013).

find that for any assumed death-line the statistical distribution of deathline proximity for ordinary nulling pulsars is very different from that of the RRATs. 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). 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 (Konar *et al.* 2016).

A glitch is a timing irregularity of radio pulsars, marked by a sudden increase in the spin-frequency ν which may sometimes be followed by a relaxation towards its unperturbed value. These are probably caused by sudden and irregular transfer of angular momentum to the solid crust of the neutron star by a super-fluid component rotating faster; or by the crust quakes. It has been suggested that the bimodality seen within the range of glitch values actually pertain to these two separate mechanisms (Yu *et al.* 2013). Our statistical analysis supports the conjecture that there exist more than one glitch mechanism corresponding to different intrinsic energies. We suggest that mechanisms responsible for glitches are perhaps different for different energy regimes, originating in different regions of the star (Konar & Arjunwadkar 2014).

A detailed discussion about the statistical studies can be found in Arjunwadkar *et al.* (2016).

3.3 *Radio pulsars: Synthesis studies*

Population synthesis study is the effort to understand the cumulative properties of neutron stars in different 'classes' and to reveal the underlying physics behind such observed properties. One simple 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 *et al.* 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 the detailed 'full dynamical' method becomes unavoidable (Bhattacharya *et al.* 1992; Faucher-Giguère & Kaspi 2006; Story *et al.* 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 *et al.* 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 *et al.* 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 an open avenue, which is likely to shed more light on the physics of different sub-classes of rotation powered pulsars (for example, the RRATs) which are yet to be understood properly. Population synthesis will be useful for other areas of research as well, including gravitational wave astronomy, short GRBs etc. Moreover, there is enough scope of employing population synthesis methods to other 'classes' of neutron stars, e.g., APPs.

It is expected that the SKA will lead to discoveries of more RPPs (Smits *et al.* 2009, 2011). This larger data set will enable us to test existing and future population synthesis studies as well as explore evolutionary pathways. While phase-1 of the SKA-low is proposed to have 500 simultaneous beams, the SKA-mid will have 1600 beams within its large primary beam. The full SKA is proposed to have even larger number of beams. This makes the SKA a rapid survey instrument. With up-to 1800 s *dwell time* (length of integration per position) and 96 MHz instantaneous bandwidth at SKA1-low and 300 MHz instantaneous bandwidth at SKA1-mid, the first phase of SKA is expected to find about 10000 new pulsars with 1500 MSRPs. The full SKA is expected to triple the number of these discoveries (Keane *et al.* 2015). These discoveries are likely to uncover new classes of neutron stars including pulsars with stellar mass black hole (SMBH) companions, pulsars within a parsec of Galactic Centre and probably even some unexpected/unknown sub-classes. The unprecedented increase in the sample is likely to result in finding more *missing link* objects to firmly establish the evolutionary pathways between these classes.

The GMRT has been widely used for RPP surveys (Freire *et al.* 2004; Gupta *et al.* 2005; Joshi *et al.* 2009) at low frequencies. The recent upgrade provides an opportunity to use 200 MHz instantaneous bandwidth between 300–500 MHz for a rapid survey of the sky, using the GMRT's $\sim 80'$ primary beam. The frequency range for such a survey overlaps that of the SKA1-low and Band-1 of the SKA1-mid, and can provide useful inputs for the eventual SKA1 pulsar surveys with both the instruments. At present using an incoherent array of 25 antennas of the GMRT, with 4096 channels across the $300-500$ MHz bandwidth, a sampling time of about 80 μs and a dwell time of 300 s, the entire northern sky can be covered in about 1100 h with the uGMRT. Even with a modest 200–250 h of observing time per year, it can be completed well in advance of the commencement of science observations for the phase 1 of SKA. This survey is expected to discover something like 800 new normal pulsars and 20 new MSRPs according to simulations from population synthesis models (Bates *et al.* 2014). Evidently such a study, besides providing immediate science returns for the uGMRT, has the potential for becoming a pathfinder survey for pulsar science with the SKA, commensurate with the *'pathfinder'* status of the uGMRT. The expected distribution of pulsars from this survey is indicated in Fig. 2.

A survey with much higher sensitivity can be performed using the fourteen antennas in the inner central square of the GMRT in a phased array. This would have a potential of discovering 2000 ordinary and 90 millisecond pulsars with 180 s dwell time. Such a survey would require half the observing time with much larger science returns. However, for a greater survey speed, several beams in the sky are needed and a new multi-beam receiver needs to be developed for this purpose. Either way these proposed surveys will allow for devising new observing and search strategies. Moreover, properly designed, these surveys would help train young students thus being useful both as a manpower development effort for the SKA as well as preparing the community for fruitful exploitation of data from the SKA pulsar surveys in future.

3.4 *Black-widows and red-backs: Super-Jupiter companions*

Observation of molecular lines in the ablated wind of super-Jupiter companions of black-widow and/or red-back pulsars can provide an interesting line of investigation into the physics of these systems. The black-widow and the red-back pulsars are binary MSRPs but are so named because they are in the process of destroying their companions through strong pulsar winds. The first black-widow pulsar observed is PSR B1957+20 (Fruchter *et al.* 1988, 1990), a millisecond radio pulsar ($P_{\rm spin} = 6.2$ ms) ablating its companion in a binary system ($P_{\rm orb} = 9.17$ h). It has been suggested (Kluzniak *et al.* 1988; Phinney *et al.* 1988) that strong gamma-ray irradiation

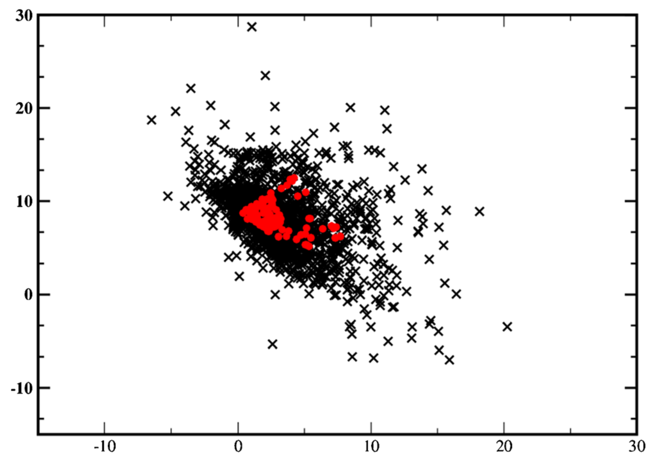

Figure 2. Distribution of expected RPP discoveries projected onto the Galactic plane. The Galactic centre is at the origin and the axes logarithmic distance in units of Kpc. Ordinary radio pulsars (PSR) are marked with a black ×, while the millisecond radio pulsars (MSRP) are marked with filled red circles. This is from a proposed survey of the north Galactic plane obtained using population synthesis methods. The proposed survey will use an incoherent array of 25 uGMRT antennae with the new 300–500 MHz receivers, commissioned in the recent upgrade.

from the millisecond pulsar drives the wind from the companion star and gives rise to a bow shock between the wind and pulsar magnetic field. The pulsar is likely to be left as an isolated millisecond pulsar after few times, 10^8 yr. The observability of these binary pulsars in the black widow state implies that the lifetime of this transitory phase cannot be much shorter. Given the strong pulsar radiation and the relativistic electron–positron outflow ablating its companion to drive a comet-tail like wind, it is feasible to search for absorption lines in radio spectra.

Detection of OH line absorption through radio line spectroscopy in intra-binary space around a few millisecond pulsars has recently been suggested (Ray & Loeb 2015). A detection may lead to a better understanding of past evolutionary history of such systems as well as the composition of the companions themselves. The knowledge may help us to discern formation scenarios of ultra-low mass companions of pulsars. Detection of OH lines would lead to constraints on the present state, e.g. the mass and radius of the companion. OH is usually formed by the dissociation of H_2O molecule, so it is often considered a proxy for water, the most sought after molecule in the exoplanet context. Black widow and red-back pulsars have the characteristics that make them good targets for OH line detection observations since pulsar timing and optical observations allow us to determine their geometry, including the eclipsing region, well and their short orbital periods allow for repeated observations over many orbits within reasonable time-lines to build up gated exposure time on the radio pulses near eclipse ingress and egress. The geometry for a pulsar beam passing through the ablated wind of a companion orbiting a typical black widow pulsar is shown in Fig. 3.

The intended targets would have to include *binary, millisecond* pulsars with high spin-down power and moderate radio flux densities, with ultra-low mass (or even comparable to Jupiter mass) companions in close orbits ($P_{\rm orb} \sim 2-14$ h). Their

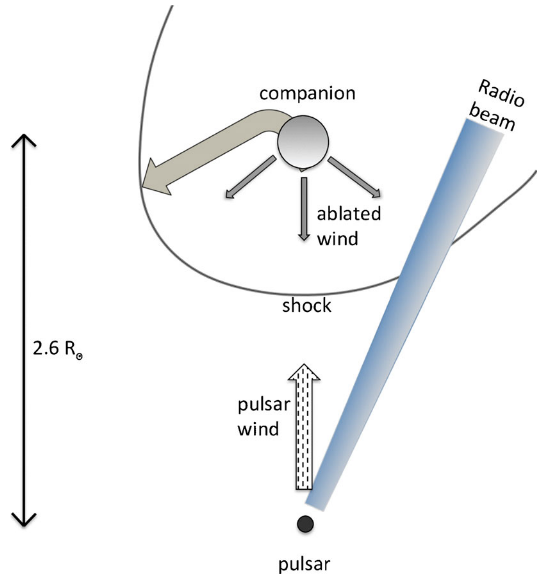

Figure 3. The geometry of a pulsar beam passing through the ablated wind from the super-Jupiter companion orbiting a black widow pulsar. The wind may be rich in oxygen if the companion is the remnant of a star that has generated carbon or oxygen during its own evolutionary process.

moderate mean flux densities and their small orbital dimensions would make them good targets for OH absorption studies against their pulsed flux. It has been argued that even with existing telescopes like GBT, Arecibo and Parkes it should be possible to detect the OH line from black-widow and red-back pulsars (Ray & Loeb 2015). Such lines in absorption spectroscopy or maser emission in the ISM has already been detected for a few pulsars (Stanimirović *et al.* 2003; Weisberg *et al.* 2005; Minter 2008).

Future telescopes like the Square Kilometre Array (SKA) will have typically ten (SKA1-Mid) to hundred times (full SKA) flux sensitivity compared to GBT. With SKA-1 increased sensitivity in L-band (Band 2) using low noise amplifiers, it will be possible to carry out such molecular line detections down to a pulsar mean flux density level of 0.7 mJy or lower, opening up several other known pulsar targets for similar studies. In addition, many newly discovered pulsar targets will become available for studies of composition of the winds from the companion.

4. The evolution

4.1 *In HMXBs*

While the Double Neutron Star (DNS) 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 stars, 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 the formation of DNS 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 only a handful of such systems have been followed so far. Measurements of orbital decay of a large number of HMXBs are expected to be performed with Astrosat and other planned X-ray timing instruments.

To date only a single double pulsar system is known (Burgay *et al.* 2003; Lyne *et al*. 2004). Twelve DNS binaries, including the double pulsar system, form a rather small sample of such systems (Beniamini & Piran 2016). These allow for accurate mass measurements and potentially radius measurement as well, making them important candidates for constraining the equations of state, as discussed later (see section 5.1). X-ray measurements of the HMXBs would have an impact on estimating the rates of DNS and NS-BH binaries. This would affect searches with the SKA and eventually have an impact on the event rate estimate of gravitational wave detectors as well.

4.2 *In LMXBs, 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.* 2015; Papitto *et al.* 2013). Each of the three systems is a red-back 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-red-back 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.

4.3 *Evolution of the magnetic fields*

As mentioned in section 3.1, the evolution of magnetic field is one of the central ingredients in understanding the interconnections between different observational classes of the neutron stars. The evolution of the magnetic field in accreting neutron stars has been of sustained interest to a number of Indian scientists over the years. The following summarizes the recent efforts in this area which is expected to get a fillip with the expected increase in the number of transient pulsars (like black-widow and red-back, for example) and other categories in the SKA era.

In accreting neutron star binaries, matter is channelled along the magnetic field lines from the accretion disc to the poles forming an accretion column (Ghosh & Lamb 1978; Basko & Sunyaev 1976). The matter accumulated at the base of such accretion columns can significantly distort the local magnetic field (Melatos & Phinney 2001; Payne & Melatos 2004; Mukherjee & Bhattacharya 2012). Understanding the evolution of the accretion mounds and its effect on the neutron star's magnetic field will help address several open questions, which can be broadly classified into two categories:

(1) *Short term evolution of the accretion column*: The accreted matter will be confined by the magnetic field at the polar cap of the neutron star. However, beyond a threshold accreted mass, pressure driven plasma instabilities will cause the matter to break out of the magnetic confinement and spread over the neutron star (Mukherjee *et al.* 2013a, b; Ferrigno *et al.* 2013). Such dynamic processes occurring over short time scales (local Aflven times and accretion time scales) will leave a significant imprint in the local magnetic field topology. The dynamics of the spreading of matter from accretion columns remain an unresolved question, both from observational and theoretical perspectives.

    The local field topology can be directly probed from observations of Cyclotron Resonance Scattering Features (CRSF) from X-ray observations (Harding & Lai 2006). Distortions in the magnetic field is also expected to cause to complex line shapes in the CRSF profiles (Mukherjee & Bhattacharya 2012; Mukherjee *et al.* 2013a). Due to limited capabilities of existing instruments, there have been only a few detections of asymmetric line profiles (Pottschmidt *et al.* 2005; Fürst *et al.* 2015). Future observations with Astrosat and NuStar is expected to constrain the physics of accretion columns further. Theoretical understanding of the interplay of radiation pressure and in-falling matter and its effect on continuum radiation is also currently lacking. Such studies will help better constrain models of accretion columns which is currently used to model X-ray observations.

(2) *Long term evolution of the magnetic field*: The low magnetic field strengths of millisecond pulsars have long been attributed to recycling due to accretion (Bisnovatyi-Kogan & Komberg 1974; Romani 1990). However, the exact mechanism of field decay is still unclear. Although diamagnetic screening due to field burial has been proposed (Melatos & Phinney 2001; Payne & Melatos 2004; Choudhuri & Konar 2002; Konar & Choudhuri 2004) as a possible mechanism, there is no clear consensus on whether large scale field burial is possible without re-emergence (Cumming *et al.* 2001) or if MHD instabilities (Mukherjee *et al.* 2013a, b) may inhibit deformation of field lines required to reduce the apparent dipole moment. Accretion enhanced ohmic decay of magnetic fields (Konar 1997; Konar & Bhattacharya 1997, 1999) is another plausible mechanism that may reduce the magnetic fields to values observed for millisecond pulsars. However the current works do not address in detail the dynamics of spreading resulting from magnetic channelling of matter onto the neutron star, which needs to be addressed. Such studies will also help understand the evolution of magnetic field strength of accreting neutron stars from $\sim 10^{12}$ G to $\sim 10^{8}$ G in millisecond pulsars.

Recently two accretion powered pulsars have shown evidences of long term evolution of the magnetic field through evolution of the CRSF centroid energy. Her X-1 has shown long term evolution of the CRSF independent to other observables both in the form of a sudden jump followed by a gradual decay (Staubert *et al.* 2014; Klochkov *et al.* 2015). 4U 1538−522 also shows signatures of an evolving CRSF energy (Hemphill *et al.* 2016).

5. The interior

5.1 *State of the matter*

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 of 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 for neutron stars than that for the nuclear EoS (Glendenning 1996).

Observed masses and radii of neutron stars are direct probes of compositions and EoS of the 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 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 etc. were measured in several binary pulsars. Currently the accurately measured highest neutron star mass is $2.01 \pm 0.04 M_\odot$ (Antoniadis *et al.* 2013). This puts a strong constraint on the EoS of neutron star matter. Those EoS which can not satisfy the $2M_\odot$ constraint, are ruled out (Banik *et al.* 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 the 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 per cent 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 by 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 CC-SNe simulations, neutron star mergers and understanding the appearance of strange matter in the early post bounce phase of a CC-SNe (Banik *et al.* 2014).

The spin-off from the measurement of moment of inertia in the SKA era will be manifold. 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 super-fluid 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 super-fluid with the crust, is taken into account, a larger angular momentum reservoir is needed for observed glitches (Andersson *et al.* 2012). Consequently, the required super-fluid moment of inertia exceeds that of the super-fluid crust. This indicates that some part of the super-fluid core would contribute to pulsar glitches. It would be worth investigating the super-fluidity in neutron stars in general and the super-fluid 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 modelling of the EoS of dense matter and mass–radius relationships of (non)rotating neutron stars and will contribute immensely in the science program of the SKA.

5.2 *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 *et al.* 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 *et al.* 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).

6. The magnetosphere

6.1 *Radio pulsars*

A majority of the known neutron stars are radio pulsars, and have been detected via their radio emission. Soon after the discovery of the first pulsar (Hewish *et al.*

1968), it became clear that the pulsed nature of the received signal is likely due to a misalignment of the rotation and the magnetic axes of the pulsar (Radhakrishnan & Cooke 1969). Yet, a complete understanding of the underlying physical mechanisms responsible for the radio emission is far from complete.

The key to the pulsar puzzle lies in a critical understanding of the emission region geometry through a comparison of the high time resolution pulse data and high-sensitivity precision polarimetry with quantitative theoretical predictions. One of the limitations has been the lack of precision data. The radio emission region of a pulsar is small and it is at an altitude of a few hundred kilometres depending on field geometry. 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 one dimension, and quantize the 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. An extreme antithetical model is one in which the emission is infinitely beamed radiating tangentially to the local magnetic field lines (Gangadhara 2004).

The sensitivities and the ranges of operating frequencies of the present instruments are such that these are sufficient only for certain specific magnetospheric studies. But there exist other areas of investigation which are possible only with sufficient increase in sensitivity that will be facilitated by SKA. A subset of studies related to the pulsar emission mechanism, broadly divided on the basis of the timescales involved and the extents of the emission regions, are discussed below:

(1) *Phenomena at single pulse timescales*: There are primarily 3 kinds of intriguing phenomena observed in single pulse sequences of a significant number of pulsars — pulse-nulling, sub-pulse drifting and mode-changing. Nulling is an interesting phenomenon wherein the pulse suddenly disappears, implying possibly a complete cessation of emission or emitted flux density below the detection sensitivity of current generation telescopes. Recent studies exploiting simultaneous multi-frequency observations using different telescopes suggest that the magnetospheric changes responsible for observed nulling occur at a global scale (Gajjar *et al.* 2014a). Underlying periodicities and clustering of nulls and bursts in few strong pulsars indicate the presence of a stochastic Poisson point process (Gajjar *et al.* 2012, 2014b). Detecting nulls with duration of one or only a few pulse periods has been possible only for bright pulsars. The high sensitivity of SKA will help in (1) detection of any faint emission during the apparent nulls, and (2) studying the nulling properties of faint pulsars. The different bands available in SKA-low and SKA-mid would be very useful to extend simultaneous multi-frequency observations of a much larger sample of pulsars. The increased sensitivity will also help in studying the emission properties of pulsars when the transition from one profile mode to the other takes place. Both these aspects will provide crucial inputs to modelling of physical theories explaining these phenomena.

Sub-pulse drifting or sub-pulse modulation involves intriguing modulations in single pulse components, which indicate towards physical processes occurring at a range of timescales — from a few milliseconds to a few hundreds of seconds. A phenomenological model (carousel model) to explain sub-pulse drifting was suggested (Ruderman & Sutherland 1975) at a very early stage. The carousel model was modified to address some of the observed inconsistencies (Gil & Sendyk 2000). Significant observational advances have also been made in this direction. In some bright pulsars, the sub-pulse drifting has been shown to be in phase from 300 to 1400 MHz (Joshi 2013). Several pulsars have been studied in detail, with some studies providing strong support to the above carousel model (Vivekanand & Joshi 1999; Deshpande & Rankin 1999, 2001; Asgekar & Deshpande 2005) while the others indicating towards inconsistencies in the model (Edwards *et al.* 2003; Maan & Deshpande 2014). Some other models also have been proposed (Clemens & Rosen 2004, 2008; Jones 2013, 2014) to explain the sub-pulse modulation in pulsars. Further observational progress on this front, like systematic tests of various proposed models, requires high sensitivity and good quality full-polarimetric measurements of pulsars at wide range of frequencies. Such measurements are possible with the existing telescopes only for a sample of bright pulsars. SKA will make it possible to extend these studies to even the fainter pulsars, and hence, aid in developing a robust physical model applicable to majority of pulsars.

(2) *Phenomena at micro- and nano-second timescales*: Micro-structures (less-ordered intensity variations with time-scales 1 to 500 μs) are seen in nearly all bright pulsars, but no consensus has been reached as to their origins. It is suspected that these are tied to plasma dynamics within the emission regions. Detection and study of micro-structures obviously needs detection of single pulses with sufficiently high signal-to-noise ratios (S/N).

Giant pulse (GP) emissions – a phenomenon currently known to be exhibited by only about a dozen radio pulsars (out of nearly 2500 known) – are short-duration (sometimes as short as a few nanoseconds) burst-like sporadic increases of individual pulse intensities (Hankins *et al.* 2003). The peak flux densities of GPs can exceed those of regular individual pulses by factors of hundreds or even thousands. Although several mechanisms have been proposed for the observed GP emission, there is no satisfactory answer for a question as simple as: what are the identifying characteristics of the pulsars that emit giant pulses?

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. The increased sensitivity facilitated by SKA will help in detection and study of micro-structures as well as giant pulses from a statistically large number of pulsars. The purity of the polarization measurements of such detections will also provide crucial help in localizing the physical emission regions, and hence, in understanding the emission mechanism of these features.

(3) *Ultra-wide bandwidth, ultra-high time resolution observations*: They 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.

(4) *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.

(5) *Polarimetry*: 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. 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? Although calibration techniques for accurate polarimetry are now well known, attention must be paid to the polarization characteristics of new wide-band 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.

(6) *Pulsar emission physics*: The SKA is expected to greatly help us to address some of the key problems in pulsar physics.

- *How can we construct the 3D structure of pulsar emission beam?* Currently the 3D structure of pulsar emission is not clear whether it is conal or patchy. There are arguments for concentric rings near and around the magnetic field axis (Rankin 1983, 1993; Gangadhara & Gupta 2001; Mitra & Rankin 2002) or random locations in the beam rather than in some coherent conal structure (Lyne & Manchester 1988). Gangadhara and Gupta (2001) have further showed that at any given radio frequency the emissions close to magnetic axis comes from lower altitude compared to the conal emissions. The individual pulses that build the stable profile show enormous diversity in their overall characteristics. One needs to understand how the single pulses averaged to a stable mean profile. Deduction of 3D structure of the pulsar radio beam and how it forms from individual pulses, comprises a major step in revealing the pulsar radio emission mechanism. One has to study in a large survey the beam shapes of young and old pulsars to resolve this issue.
- *Modelling of polarization of pulsar profiles*: Both the emission process and the viewing geometry set the polarization state of the pulsar radio emission, which is expected to be further modified by the propagation effects in pulsar

magnetosphere. Gangadhara (2010) has developed a polarization model of pulsars based on curvature emission, and shown how the S-type polarization angle swing correlates with the sense of circular polarization. Further, Kumar & Gangadhara (2012a, b, 2013) have generalised the polarization model to include aberration-retardation and polar cap currents. Propagation effects have been observed, the most prominent being orthogonal modes of polarization, which are generated in the magnetospheric plasma. Understanding the nature and origin of orthogonal polarization modes in magnetospheric plasma is crucial in understanding pulsar emission physics. The observing capabilities of SKA is expected to resolve the issue of the origin of orthogonal polarization modes: intrinsic to the emission process or generated by the propagation effects.

(7) *Continuous/unpulsed/off-pulse emission*: Presence of a continuous emission component, i.e., emission in the off-pulse regime or far from the main pulse in the profile, has been long looked for. It is only recently that such emissions have been made from the pulsars B0525+21 and B2045−16 (Basu *et al.* 2011). A magnetospheric origin of such off-pulse emission raises questions about the location of the emission region. These detections have been possible due to the availability of a fast sampling time (∼125 ms) in the interferometric mode of the GMRT. GMRT's fast sampling time is adequate to resolve the off-pulse emission only for a handful of pulsars, that too very coarsely. The strength of the off-pulse emission has also been found to be only about 1% of that of the main pulse, demanding a very high sensitivity instrument. The SKA, with its high sensitivity, possible gating in 100 bins across the pulsar period and large frequency coverage will be an ideal and much-awaited telescope to carry out the off-pulse emission searches and studies.

Apart from the known emission components detailed above, very faint radio emission from some of the gamma-ray pulsars, earlier considered to be *radio-quiet*, have been detected. Two of these gamma-ray pulsars, J0106+4855 and J1907+0602, have been found to emit in radio with L-band flux densities below 10 μJy (Pletsch *et al.* 2012; Abdo *et al.* 2010). Furthermore, another gamma-ray pulsar, J1732−3131, has been found to emit at low radio frequencies (Maan *et al.* 2012; Maan & Aswathappa 2014; Maan *et al.* 2016) with an upper limit on its flux density at L-band being 50 μJy. Unusual radio emission from these gamma-ray pulsars might also be detected in the form of 'giant-pulses' or bursty emission (Maan 2015). Detection of such faint or bursty radio emission from these pulsars might suggest the presence of radio emission from all the gamma-ray pulsars that is below the detection sensitivity of current telescopes. The upcoming telescopes SKA and FAST, with their unprecedented sensitivities, might uncover such faint emission from these pulsars, and hence, a new class of faint radio pulsars. Detection of the faint emission with polarimetric information will also play a crucial role in understanding the location of the gamma-ray emission regions relative to the radio emission regions.

6.2 *Fast radio bursts*

Fast Radio Bursts (FRB) are a recently discovered (Lorimer *et al.* 2007; Thornton *et al.* 2013; Spitler *et al.* 2014a; Ravi *et al.* 2015) class of radio transients which are of very short duration (∼ 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 *et al.* 2013) or neutron stars (Totani 2013), collapse of supra-massive neutron stars (Falcke & Rezzolla 2014), exploding black holes (Barrau *et al.* 2014), dark matter induced collapse of neutron stars (Fuller & Ott 2015), 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 interest recently. 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'.

7. Gravitational physics: 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, 2004, 2010; Kramer *et al.* 2006). 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 *et al.* 2005; Kiel & Hurley 2009), globular clusters (Sigurdsson 2003), and near the Galactic Centre (Faucher-Giguère & Loeb 2011) have been presented. If NS–BH binaries have small orbital periods (around a day), as predicted (Pfahl *et al.* 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).

The central region of the galaxy has a dense population of visible stars. It is quite likely that compact objects, such as black holes (BHs) (Morris 1993; Freitag *et al.* 2006), neutron stars and Intermediate Mass Black Holes (IMBH) (Portegies Zwart *et al.* 2006) may also be present there. The discovery and timing of millisecond pulsars in the centre of our galaxy (hereafter GC) may allow us to detect long wavelength gravitational waves (GWs) emitted from the SgrA* region due to large mass black-holes orbiting the central super-massive black-hole (SMBH). This will allow us to 'gravitationally probe' these crowded regions which are usually obscured in the electromagnetic channels (Kocsis *et al.* 2012). The GW signal generated by a population of objects (the 'foreground') is smooth if the average number per Δf frequency bin satisfies $\langle \Delta N \rangle \gg 1$. The GW spectrum becomes spiky (with $\langle \Delta N \rangle \leq 1$) above a critical frequency $f_{\rm res}$ that depends on the number of objects within 1pc of the GC and on the timing observation span. Sources within $r_{\rm res}$ generate distinct spectral peaks above frequency $f_{\rm res}$. These sources are *resolvable*. The GW spectrum transitions from continuous to discrete at higher frequencies inside the Pulsar Timing Array frequency band. If pulsars are observed repeatedly in time for an observation span $T = 10$ yr and with an interval $\Delta t = 1$ week, this can probe the range of GW frequencies: 3×10^{-9} Hz (3 nHz) $< f < 3 \times 10^{-6}$ Hz (3000 nHz). The cosmological GW background from the whole population of massive black hole binaries (MBHBs) is actually an astrophysical 'noise' for the purpose of measuring the GWs of objects orbiting SgrA*. The characteristic GW amplitudes (either of a stochastic background or of a resolvable source) can be translated into a 'characteristic timing residual' $\delta t_c(f)$ corresponding to a delay in the time of arrivals of pulses due to GWs, after averaging over the sky position and polarization. The results of simulations are summarized in Fig. 4. BHs in orbit around SMBH SgrA* generates a continuous GW spectrum with $f < 40$ nHz. A 100 ns–10 μs timing accuracy with SKA will be sufficient to detect IMBHs ($1000 M_\odot$), if they exist, in a 3 year observation if stable PSRs 0.1−1 pc away from SgrA* are timed.

A large population of pulsars could be present inside the GC (Pfahl & Loeb 2004). The recent discovery of GC magnetar SGR J1745−29 in the X-ray bands with NuSTAR and subsequently in the 1.2–18.95 GHz radio bands (Bower *et al.* 2014; Spitler *et al.* 2014b) shows that the source angular sizes are consistent with scatter broadened size of SgrA* at each radio frequency. Additionally, pulse broadening timescale at 1 GHz (Spitler *et al.* 2014b) is several orders of magnitude lower than the scattering predicted by NE2001 model (Cordes & Lazio 2002). Chennamangalam & Lorimer (2014) estimated an upper limit of ∼950 potentially observable radio loud pulsars in GC. However, Dexter & O'Leary (2014) pointed out that despite several deep-radio surveys, no ordinary pulsars have been detected very close to the GC and suggest an intrinsic deficit in the ordinary (i.e. slow) pulsar population. Macquart & Kanekar (2015) distinguished two possible scattering scenarios affecting the search for millisecond pulsar search in the GC and suggesteded that in the weak scattering regime (if applicable for a large part of the GC) a substantial fraction of the pulsars (>1 mJy kpc^2 at 1.4 GHz) would be detected when observed with SKA-Mid in the X-band (∼8 GHz) and possibly a smaller fraction even with EVLA and GBT at

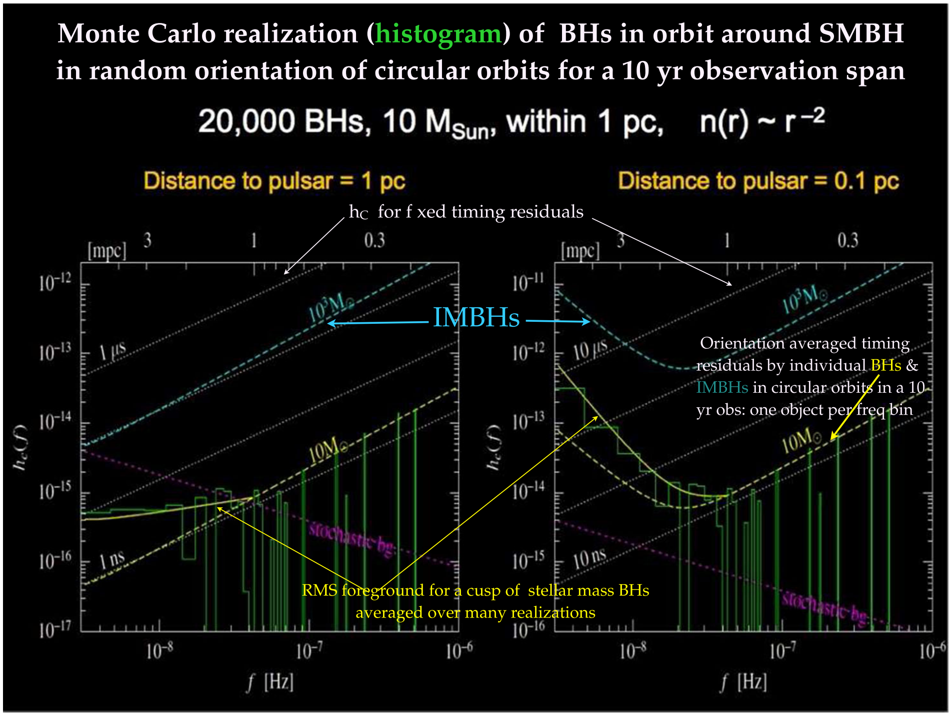

Figure 4. Detectable phase space of characteristic strain amplitude h_c and GW frequency f with pulsar timing with a probe pulsar at 1 pc (*left*) and 0.1 pc (*right*) from the Galactic Centre. Dotted white lines show the orientation-averaged h_c for fixed timing residuals measured from the probe pulsars. Yellow and cyan dashed lines show respectively the binary orientation-averaged timing residuals caused by individual stellar BHs and IMBHs on circular orbits around the SMBH in a 10-yr timing of the probe pulsar, assuming 1 object (source) per frequency bin. Green lines (histogram) show the timing residuals for a random realization of $10M_\odot$ stellar BHs in the cluster (20,000 BHs within 1 pc with number density $\propto r^{-2}$). At high f, only few bins are occupied, generating a spiky signal. At lower f, many sources overlap to create a continuous spectrum. Magenta dashed lines show the cosmological stochastic GW background which can be much smaller, especially as f increases. For other (steeper) BH population density profiles or for BH orbits with isotropic thermal eccentricity distributions, see Kocsis *et al.* (2012).

a less deep level. For the strong scattering regime however, the full high frequency (∼25 GHz) capability of the SKA on the longer term will be necessary. The detection and long term accurate timing of stable millisecond pulsars near the GC will be of interest to the Indian partners of the SKA community from multiple perspectives of probing the contents of the Galactic Centre, detecting gravitational waves and tests of strong gravity.

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 centre 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 mono-polar 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 mono-polar and dipolar gravitational waves. NS–BH systems will be better systems to detect such emissions as the combined effect of mono-polar, dipolar and quadrupolar 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 evolution of few Keplerian parameters while incorporating the effect of gravitational wave emission in a non-adiabatic manner as detailed in Damour *et al.* (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 kilometre 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 analysing 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 *et al.* (2004), Tessmer and Gopakumar (2007), Gopakumar and 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.

Super-massive black hole binaries (SMBHBs) are putative sources in nano-Hertz gravitational wave astronomy. Incoherent superposition of a large number of SMBHBs is expected to produce stochastic background signal for Pulsar Timing Arrays (PTA). Though it is unlikely to resolve the sources individually, such a possibility has been explored for $z < 2$ (Sesana *et al.* 2008; Ölmez *et al.* 2010; Ravi *et al.* 2012). The authors further study and show that with 100 pulsars, the SMBHBs can be located with 40 degree square (Sesana & Vecchio 2010). Pertaining to the early inspiral phase, the signal from such a source is monochromatic in nature. The maximum likelihood approach has been further developed to explore the feasibility to localize the SMBHB source with a PTA (Babak & Sesana 2012). Recently, we have defined the figures of merit of PTA to quantify its efficiency and probe the angular resolution ability as well as the polarization recovery of the underlying SMBHB source (Agarwal & Pai 2016). This work clearly demonstrates the idea of using PTA as a multi-detector network to detect gravitational waves from SMBHBs.

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 candidates 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.

8. Multi-wavelength studies

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 up to 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

Table 2. Pulsar studies with high sensitivity radio telescopes.

	Name and 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 3. Neutron star studies with high-energy instruments*.

	Mission	Launch date	Status	Neutron star studies
1	Astrosat	Current		Cyclotron line, KHz QPOs with large area and broad energy coverage
2	Chandra	Current		Accurate position/identification, faint source flux measurement, high resolution spectroscopy
3	Fermi	Current		Frequency evolution, accretion torque, magnetar outbursts
4	Integral	Current		HMXB outbursts, Cyclotron line evolution, Highly absorbed systems
5	MAXI	Current		Accreting NS systems, orbital coverage for spectral study of bright sources
6	NuStar	Current		Cyclotron line – new sources, spectral measurement
7	Suzaku	Current		Cyclotron line, broad band spectroscopy
8	Swift	Current		Super-giant Fast X-ray Transients, all sky monitoring in hard X-rays
9	XMM	Current		Iron line shape, high resolution and high throughput spectroscopy, M/R from line during bursts
10	NICER	(2017)	Approved	EoS, soft X-ray spectral and timing studies with large area
11	HXMT	(2017)	Approved	
12	eXTP	(2025)	Potential	Soft X-ray imaging, polarimetry, perhaps EOS & strong gravity
13	Athena	(2028)	Approved	
14	eRosita		Approved	Medium energy X-ray survey, new members/population of sources? More magnetars?
15	POLIX		Approved	Magnetic field structures, emission mechanism in accreting and young NS.

*Authentic list of current and past observatories are available at http://heasarc.gsfc.nasa.gov/docs/observatories.html 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 into why accretion from wind in these systems give different X-ray features in the form of fast transient outbursts.

Though the immediate emphasis of this document has been the impact of SKA era on neutron star research and the immediate benefits of ASTROSAT, 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 2 and 3, we present a comprehensive list of such instruments and note down the particular kind of investigations that could be undertaken using them.

9. Summary

The SKA represents the next big leap in sensitivity for radio astronomy. The neutron star science with the SKA will mainly be done through all-sky surveys, which is expected to result in tripling the current pulsar population, allowing variety of theories to be tested. It is noted that the interests of the neutron star community in India correspond closely to these SKA science goals, in regard to the pulsar astronomy. We are now beginning to define theoretical calculations/simulations as well as observational projects, keeping in mind that the community can immediately make use of the recently launched Indian X-ray instrument ASTROSAT and the upgraded GMRT (uGMRT) which has been given the SKA pathfinder status. Execution of these projects, theoretical as well as observational, would prepare the community to make appropriate use of the SKA capabilities in future.

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