Chapter 1

Introduction

1.1 Introduction

The largest building blocks of a universe are galaxies. Our observable universe is made of almost 2 trillion galaxies (Conselice et al., 2016). The basic constituents of a galaxy are the interstellar gas, dust, remnants, stars, cosmic rays, magnetic fields, and dark matter (Sparke and Gallagher, 2000). Based on their morphology, the galaxies are of three types: spiral, elliptical, and irregular. Milky Way (our galaxy) is a spiral galaxy. As the gas and molecular cloud density within the galaxy is larger than those of the intergalactic medium, the galaxies are the hosts of the star-forming regions. The galaxy dynamics are studied with its basic phenomenology, physical models, and the stellar dynamics within it (Bertin, 2014). The life span of the stars depends upon their mass, larger the mass of a star, sooner it ends its life compared to the low mass stars. The shape of a star is a result of the balance between its self-gravity and thermodynamics. Depending upon the excess of one on the other and mass of the star, the end state of a star may be the following, a) Star may die with an efficient explosion dispersing its all materials in the outer space, b) Ending as a degenerate white dwarf, c) Being converted as a neutron star or d) a black hole, representing ultimate win of the self-gravity over thermodynamics. Among these, one of the significant events that happen at the end-stage of a star is a supernovae formation. The formation of a supernova takes place in two ways: first, when a white dwarf accumulates too much matter from its companion star, it explodes and forms a supernova called Type I Supernova. In this case, the outburst is caused by the "sets off a runaway nuclear reaction" as the white dwarf is compressed due to too much mass accumulation. Second, when a star runs out of fuels at the end state of its life, it collapses to its gravitational pull resulting in a giant explosion known as Type II supernova. For the Type II supernova, the progenitor is a high mass star (several times the mass of the sun) in which once the Hydrogen and Helium run out of fuel, enough pressure of the high mass star causes Carbon fusion. In this process, heavier elements build up inside it at the center, followed by the lighter mass elements towards the outside (layer by layer), until the Chandrasekhar limit is reached and it implodes. Now core gets heated as it becomes denser and finally, implosion bounces back (off the core), and materials are expelled into the outer space, resulting in supernovae and leaving behind a neutron star. Supernovae are observed in a wide frequency range of the electromagnetic spectrum and extensively studied in the X-ray, infrared, and radio frequency observations. Few of the Supernova like 1987A and Keplar have been observed even with the naked eyes due to their very high luminosity. They are also the brightest radio source in the sky. The materials ejected in the explosion of the supernovae and the materials of the surrounding medium swept by the supernova explosion shock are cumulatively called the supernovae remnants. Their morphology is mainly classified as filled center like (Crab-like), shell-like, composite supernova remnants, and few with mixed-morphology shape (Rho and Petre, 1998). Due to the stellar feedback regulation, physical and chemical processes, the molecular part of the interstellar medium leads to the formation of stars (Draine, 2011; Hayward and Hopkins, 2016; Stahler and Palla, 2004). These newborn stars play a very significant role in the evolution of a galaxy.

1.2 The Interstellar Medium (ISM)

In the galaxy, the medium between stars consisting of gaseous, dust particles, cosmic rays, relativistic electrons, and the ambient magnetic field is called the interstellar medium (ISM). By mass, Hydrogen and Helium are the most abundant in the ISM, being 70% and 28% respectively (Bron, 2014). The rest of the ISM mass is constituted by dust and heavy mass metal elements such as Na, Ca+, Fe, Ne, Ni, etc. Based on the physical properties of the ISM, it is divided into many phases like Molecular Medium (MM), Cold Neutral Medium (CNM), Warm Neutral Medium (WNM), and Hot Ionised Medium (HIM) (Draine, 2011; Field et al., 1969; McKee et al., 2004; Wolfire et al., 1995). Cold neutral medium has temperatures of around 100K, number density $\sim$ 30 per cubic centimeter, and it fills $\sim$ 1 % volume of the ISM (Draine, 2011). Broadly, phases of the interstellar medium are studied mainly with three components CNM, WNM, and WIM (Cox, 2005; McKee and Ostriker, 1977). The neutral gas is mainly divided into two parts: Cold neutral medium (Temperature $\sim$ 100K, density $\sim$ 30 per centimeter cube and filling factor $\sim$ 1%) and Warm neutral medium (Temperature $\sim$ 10^4K, density $\sim$ 0.6 per cubic centimeter, and filling factor $\sim$ 40%) are almost in pressure equilibrium (Cox, 2005; Savage and Sembach, 1996). At the largest scale, the structure of our galaxy is spiral and traced by the emission of the neutral H I gas component (Hou and Han, 2014). The study has shown that the structure of our galactic ISM around Cassiopeia-A has shells and filaments like structures at the length scales of subparsec to parsec (Kim et al., 2008), while the model of the ISM (McKee and Ostriker, 1977) suggest that at the length scales of parsec, there exist H I clouds. In this model, the core of the cloud (CNM) is surrounded by the WNM, which itself is surrounded by the WIM, and HIM being as the outermost layer. The large scale structures of the neutral H I are probed with the help of the H I emission observations as it is detectable even using the single-dish radio telescopes. On the other hand, the study of the small scale structures is done through the absorption studies against bright background sources. To probe the wide range of length scales, selected background sources need to be extended (like supernovae remnants), which is part of this thesis. In the neutral atomic H I components, absorption studies have shown that our galaxy has structures over the wide range of length scales (from subparsec to hundreds of parsec) and the structures can be represented by the scale-invariant power laws (Crovisier and Dickey, 1983; Deshpande et al., 2000; Dickey et al., 2001; Green, 1993; Roy et al., 2010). The study of the Galactic optical depth fluctuation via the structure-function measurements towards 3C 138 has shown that the scale-invariant structures in the length scales of 5-40 au, are consistent with the results at the length scales of the sub parsec to parsecs (Dutta et al., 2014). More studies also have been done to measure the fine-scale structures on decades of length scales in the atomic interstellar medium (see Stanimirović and Zweibel (2018)).

The magnetic field is a critical determiner for the stability and hydrostatic balance of the Galactic ISM (Boulares and Cox, 1990). They are not only the primary source to support the transport of the charged particles (Prouza and Šmída, 2003; Tinyakov and Tkachev, 2002) but also the known factor which plays an important role during star formation in the molecular cloud (Heiles and Crutcher, 2005). Even though the study about the magnetic fields in ISM is far from complete, the Galactic magnetic field is found to exist on all scales (au-kpc), and there is a possibility that the small scale magnetic field and large scale magnetic fields are connected (Han, 2007). The magnetic field strength in the galaxies is of the order of μG. There have been around 60 years since the magnetic field in the ISM of Milky-Way and external galaxies have been discovered, but the questions related to their origin (except the dynamo theory) and impact on the ISM of galaxies are still open (Beck et al., 2019; Ferrière, 2005). The magnetic field amplification study in the vicinity of the Galactic supernova remnants shock has gained popularity in the last three decades. The study of the magnetohydrodynamic (MHD) turbulence has shown that magnetic field amplification is observed in the postshock medium if the preshock medium possesses density fluctuation (Giacalone and Jokipii, 2007). The implication of the magnetic field amplification in the vicinity of supernovae shocks is also studied in this thesis.

1.3 Probing the ISM

As discussed earlier, the ISM of a galaxy has many phases like MM, CNM, WNM, WIM, etc. These ISM constituents are traced by emission or absorption characteristics of their elements using the different ground-based or sky-based observing instruments. The hydrogen fills most of the ISM in the form of H2, H I, and HII. The molecular hydrogen may be probed at UV, mid-infrared and infrared. H2 is a symmetric and homonuclear molecule with no dipole moment, and it has a very week quadrupole transition, so CO is used as a proxy for probing the cold molecular H2. Lyman absorption lines and 21 cm hyperfine line are widely used to observe and probe the ISM's neutral atomic component, while recombination lines and free-free emissions are used to probe the Galactic HII (Draine, 2011). The continuum emission originating from the galaxy and supernova remnants is due to the motion of nonthermal electrons trapped in the magnetic field. The emissivity of the synchrotron emission in terms of the B_n and ν is given as

$$J_\nu = K\nu^{-\alpha}B_n^{1+\alpha} \tag{1.1}$$

Here B_n represents the magnetic field component perpendicular to the line of sight, K is the function that depends on the relativistic electron density and α is the index of the Cosmic Ray electron energy distribution. So the measurement of the correlation of the synchrotron intensity fluctuation can be used to probe the fluctuation in the magnetic field, electron density fluctuation, or both, depending upon the nature of the source of emission and its characteristics. 21 cm absorption against the bright background source can be used to study the column density fluctuation of the intervening ISM. The 21-cm optical depth in the ISM against the continuum background source is given as

$$\tau(\vec{\theta},\nu) = K \int \frac{n_{HI}(\vec{\theta},z)}{T_s(\vec{\theta},z)} \phi(\vec{\theta},\nu,z) dz \tag{1.2}$$

Here $n_{HI}(\vec{\theta},z)$ is the number density, $T_s(\vec{\theta},z)$ is the spin temperature, K is a constant and $\phi(\theta,\nu,z)$ is the line shape function. Under some model and assumption, correlation of the $\tau(\vec{\theta},\nu)$ is used to access the column density fluctuation of the ISM (Deshpande et al., 2000). Absorption studies are also used to estimates the temperature of the diffuse H I in the Milky Way by Gaussian decomposition of the absorption spectrum of the 21-cm line (Roy et al., 2013b)

The role of CO to study the MM of ISM is achieved with the help of the conversion factor of $^{11}CO_{1-0}$ brightness to H_2 column density (Liszt et al., 2010). This conversion is very important to determine the molecular column density and to understand the very basic property of the star formation (Bigiel et al., 2008; Bothwell et al., 2009; Leroy et al., 2008). In the very beginning, it was found out that the star formation rate is directly proportional to the luminosity of the $^{12}CO_{1-0}$ line (see Bayet et al. (2009) and references therein). However, today it is well known that other molecular tracers like HCN_{1-0}, HCN_{3-2}, and CO_{3-2} are a better indicator of the star formation rate than those of total H_2 content traced by $^{11}CO_{1-0}$ luminosity (see Bayet et al. (2009) and references therein). The recent study by Bayet et al. (2009) shows that the best indicators of SFR are the total CO and the CO lines with transition J=5-4,6-5,7-6.

The atomic hydrogen tracer, the 21 cm line, results from the two energy level difference caused by the spin-flip of the antiparallel to the parallel state of the proton and electron changing the magnetic moment interaction. The central frequency of this hyperfine line is 1420.405751 MHz. The detection of the CNM atomic phase is done by observing the absorption of the atomic 21-cm line against bright background sources like pulsars and supernovae remnants. The optical depth variation across the different length scales and lines of the site gives information about small scale structures of Galactic ISM. The supernovae being the target source not only gives H I absorption line but also helps to study the pc scale structure of the Galactic ISM via measurement of the optical depth fluctuations over a wide range of scales (Deshpande et al., 2000; Roy et al., 2010; Stanimirović and Zweibel, 2018). Using the same observation of the supernovae remnants, magnetohydrodynamic turbulence is also probed with the help of the two-point correlation of the synchrotron emission from them, helping to understand the magnetic structure within it over the decades of length scales (Roy et al., 2009; Saha et al., 2019; Shimoda et al., 2018). The detailed descriptions about these are presented in the next sections and chapters.

1.4 Turbulence in the ISM

The fundamental work that was initially done to quantify the statistics of the fluctuation is Kolmogorov's classical work published in 1941 (Kolmogorov, 1941). The theoretical work was to derive the energy spectrum of the turbulence, representing the energy distribution in terms of the turbulence vertices as a function of its size. The original work suggests that the energy dependence of the spectrum on the size of vertices follows the 2/3 power law, which, when converted in Fourier space, is equivalent to the -5/3 law. Chandrasekhar and Münch (1952) visualized that the interstellar medium can be considered as the made of continuous density with fluctuations over it having zero mean statistics. They use the volume absorption coefficient of the medium as the sum of the mean part and the fluctuating component of it with zero mean statistics. The correlation of the fluctuating component was found to depend only on the separation between the correlating components. They applied this model on the brightness fluctuation of the milky way and concluded that the RMS deviation in the density is 3-4 times the mean density of the medium. The model used by the Chandrashekhar can be applied to study the fluctuations in the optical depth of the ISM and hence to access the fluctuations in the H I column density of Galactic ISM indirectly. The study of the fluctuation in the H I column density helps us to understand the statistical nature of the turbulence in the ISM via fluctuations of H I column density, which has been shown playing a key role in the star formation process (Li et al., 2003). The observational results of the power spectrum from the H I emission by Crovisier and Dickey (1983) have shown that it follows the power-law with a slope of ~-3.0 up to 10kpc on the largest scale. Similar work done by Green (1993) found the power spectrum of the H I emission in our galaxy follows power-law with index ~ -2 to -3.0 up to length scale of 15kpc. Absorption study at the parsec length scales has shown that the H I column density statistics of the Galactic ISM follows the power-law index of the slope - 2.75 ± 0.25 in the Perseus arm and outer arm (Deshpande et al., 2000). The visibility-based estimator of the optical depth fluctuation has found that the power spectrum toward Cassiopeia-A, having an index of - 2.86 ± 0.10 (Roy et al., 2010). These works were later confirmed to be followed up to au scales toward 3C138 (Dutta et al., 2014). The ISM studies have shown that they have scale-invariant structures over a wide range of scales. Both observational and theoretical understanding and its implication are well discussed, reviewed, and are presented in the (Elmegreen and Scalo, 2004; Scalo and Elmegreen, 2004). The study of the ISM structures started back 60 years ago, and the model was proposed that ISM has supersonic turbulence and forms the structures at large scales, while the structures at small scales dissipate the energy due to atomic viscosity, injected at large scales. Later through the statistical model (Münch and Chandrasekhar, 1952) and absorption studies of the starlights by metal elements (Binney and Merrifield, 1998) shed more light on the Galactic ISM, and it was found that the milky way has clumpy structures. A numerical study by Li et al. (2003) has shown that turbulence plays a key role in the process of star formation, while Vázquez-Semadeni et al. (2003) also have shown that the clumpy structures resulted from the turbulence collapses and forms the protostars.

Though the reason behind the origin of the Galactic magnetic field is not very clear except dynamo theory (Beck et al., 2019), still there is no doubt that the magnetic field is the important factors that affect the star formation from the molecular cloud and its evolution (Hennebelle and Inutsuka, 2019). The study of the magnetic field on the initial mass function (IMF) or the star formation rate (SFR) is studied in (Krumholz and Federrath, 2019). Even though the effect of the magnetic direct on the SFR or IMF may not be quite high compared to the non-magnetized regime, but their indirect effect via interaction with supernovae, radiative heating, photoionization, etc. could have a very significant effect (Krumholz and Federrath, 2019). One of the essential ISM candidate that affect its evolution and enrichment is the supernovae remnants. The access of the magnetic field and its fluctuation in the SNR is done by observing the synchrotron emission from it. The accessed magnetic field is separated into two components, mean and fluctuation components, over mean through the observation of synchrotron intensities. The study of the shape of the magnetic energy spectrum in the SNR is important to study the possible effects of the magnetohydrodynamic turbulence on the acceleration of the cosmic rays process and mechanism in the SNRs. The different numerical and theoretical studies of magnetohydrodynamic turbulence (Brandenburg and Subramanian, 2005; Cho and Lazarian, 2003; Cho and Vishniac, 2000a,b; Goldreich and Sridhar, 1995; Inoue et al., 2012; Lazarian, 2006; Lazarian and Vishniac, 1999; Vladimirov et al., 2009; Xu and Lazarian, 2016), as well as the studies from the observation (Roy et al., 2009; Saha et al., 2019; Shimoda et al., 2018), are done to account for the questions related to the shape of the MHD spectrum, but the effect of the magnetic field through the study of the spectrum of the magnetic field in SNR needs more extensive study.

The most commonly used tools are the autocorrelation function, power spectrum, and structure-function to study the scale-invariant structures. For an isotropic and homogenous scaler filed O, autocorrelation function $\xi_o(|\delta\mathbf{r}|)$ is defined as

$$\xi_o(|\delta\mathbf{r}|) = \langle O(r)O(\mathbf{r}+\delta\mathbf{r})\rangle \tag{1.3}$$

Angular bracket in the above equation represent the ensemble averaging. The Fourier transform of this autocorrelation function $\xi_o(|\delta\mathbf{r}|)$ is known as the power spectrum $P_o(k)$, which is defined as

$$P_o(k) = \int d\mathbf{r} e^{i\mathbf{k}.\mathbf{r}} \xi_o(|\delta\mathbf{r}|) \tag{1.4}$$

Where k=$|\mathbf{k}|$. If the fluctuations are scale invariant, both autocorrelation function $\xi_o(|\delta\mathbf{r}|)$ and power spectrum $P_o(k)$ will have a power-law i.e. $P_o(k) \sim k^{\alpha}$. Here α is the power-law index of the power spectrum and used as a quantifier of the fluctuation. These fluctuations are also studied by the second order structure function $S_2(|\delta\mathbf{r}|)$, defined as

$$S_2(|\delta\mathbf{r}|) = \langle |O(r) - O(\mathbf{r} + \delta\mathbf{r})|^2 \rangle \tag{1.5}$$

This second order structure function $S_2(|\delta\mathbf{r}|)$ and autocorrelation function $\xi_o(|\delta\mathbf{r}|)$ are related to each other as follows

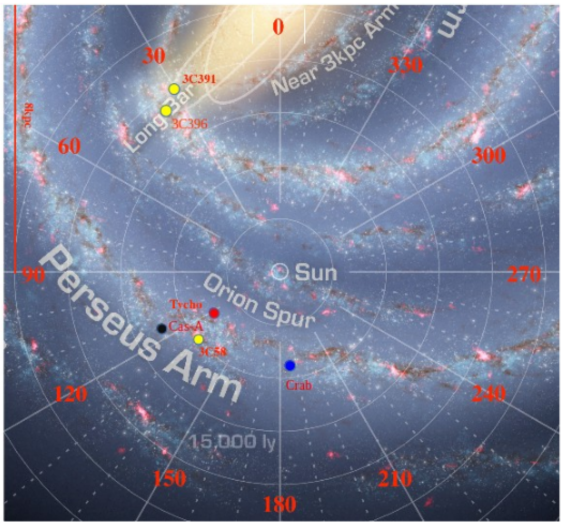
$$S_2(|\delta\mathbf{r}|) = 2(\langle O^2(\mathbf{r}) \rangle - \xi_o(|\delta\mathbf{r}|)). \tag{1.6}$$

Roy et al. (2009) and Saha et al. (2019) have measured the power spectrum of the synchrotron intensity fluctuations in the SNRs Cassiopeia-A, Crab Nebula, Keplar, and have found the power-law index -3.24 $\pm$ 0.03 for Cassiopie-A and Crab while, Keplar supernova has the broken power law and with a power-law index of -2.84 $\pm$ 0.07 and -4.39 $\pm$ 0.04. The statistics of the fluctuation of the synchrotron intensities in Tycho's SNR by Shimoda et al. (2018) in physical space are found to be Kolmogorov like. We will use the autocorrelation function to quantify both the statistics of the H I column density fluctuation of the CNM phase of the ISM as well as magnetohydrodynamic turbulence in SNRs.

1.5 This Thesis

The interstellar medium of our galaxy is probed at the scales of the astronomical unit (au) to parsec in absorption studies. Studies at the parsec length scales have shown that the H I column density statistics follow the power-law index of the slope - 2.75 ± 0.25 in the Perseus arm and outer arm (Deshpande et al., 2000). Roy et al. (2010) used the visibility-based estimator to measure the opacity fluctuation power spectrum toward Cassiopeia-A and found that the slope of the power-law index in Perseus arm toward Cassiopeia-A is - 2.86 ± 0.10. These works were later confirmed to be followed up to au scales toward 3C138 (Dutta et al., 2014). On one side, where work done on these structures have shown that they follow scale-free power-law from subparsec to parsec length scales (Crovisier and Dickey, 1983; Deshpande et al., 2000; Dickey et al., 2001; Green, 1993) , at the same time structures on the fine scales also have been observed (Brogan et al., 2005; Dieter et al., 1976; Faison and Goss, 2001; Lazio et al., 2009; Stanimirović et al., 2010). However, if there is any connection between these two length scales, still not clear and needs to be studied extensively. Study of the Galactic structures with the help of the southern pulser observations along different Galactic line of sight has shown the rare occurrence of the tiny structures (Johnston et al., 2003); this also gives rise to the questions that whether these small scale structures are short-lived or they are common at different places and directions in our galaxy? If they are common, then what are their length scales? Do they represent any physical process? What is the mechanism of the dissipation of the ISM? Do these small scale structures have any effect on the star formation process? Along with the above questions, it is also expected that the structures of the Galactic ISM be different in different directions. To answer these questions, we need to map the Galactic ISM structure in different directions. One of the objective of this thesis includes to formulate the relation between the statistics of the H I optical depth and column density fluctuation, and then map the CNM phase of the Galactic ISM through the H I column density power spectrum and search the answers for the above questions. To survey the H I column density (via absorption studies) power spectrum, we use the supernovae remnants as a background source because they are the extended source and are in good numbers across our galaxy. In an attempt to make a sample of supernovae remnants for this study, we find that the supernovae remnants Cassiopeia-A, Crab Nebula, Tycho, 3C58, 3C391 and 3C396 can be considered as a first sample based on their observation time limit, declination, position toward the galactic center and size. The details about their position, type, radio flux, etc. can be found in Green (2014). Figure 1.1 is a sketch of our galaxy showing the position of these 6 supernovae remnants and the corresponding galactic arms from which absorptions were expected, and the spectral power description was planned to be measured. The results from the Cassiopia-A already has been published, and the Crab Nebula is observed. So we wrote the GMRT proposals for the observation of the two other supernovae remnants Tycho and 3C58, and observed them in September 2018 and January 2019, respectively.

The observation of the supernova remnants also allows us to study the magnetohydrodynamic turbulence in them. Supernova remnants are believed to be the Galactic object that can accelerate Cosmic Rays up to knee energy through the diffusive shock acceleration (DSA) mechanism (Bell, 1978, 2004) and (Blandford and Ostriker, 1978). If statistics of the magnetic field disturbances is of trans-Alfvenic nature (Goldreich and Sridhar, 1995), under the quasilinear theory, the maximum energy of the cosmic ray protons for the SNRs Cassiopeia A and Tycho is found to be very close to the knee energy (Parizot et al., 2006). However, observational magnetic energy spectrum needs to be drawn if we need to access the shape of the magnetic energy spectrum. On the other hand, there is debate in the literature about the shape of the magnetic energy spectrum in SNRs, whether it is single power-law (Goldreich and Sridhar, 1995), broken power law (see Lazarian and Vishniac (1999), Cho and Lazarian (2003), Lazarian (2006), Xu and Lazarian (2016)) or spectrum with discrete peaks (Vladimirov et al., 2009). This question also requires the study of



Name of Suoernova	Galactic arm
Cassiopiea-A	Perseus arm & Local arm
Crab Nebula	Perseus arm & Orion spur
Tycho	Orion spur
3C58	Perseus arm & Orien spur
3C391	Centaurus & Sagittarius arm
3C396	Centaurus & Sagittarius arm

Fig. 1.1 : Left: The figure shows the Galactic positions of the six supernovae remnants along with their names. Right: The corresponding Galactic spiral arms are also shown, from which H I absorption is expected toward these remnants. The left figure is taken from Annu.Rev.Astron.Astrophys(2012), originally made by R. Hurt (in collaboration with R. Benjamin) and available in Churchwell et al. (2009). The figure of Galactic structures (in the background) first appeared in Astronomical Society of the Pacific (Copyright 2009, Astron.Soc.Pac.)

observational magnetic energy spectra in SNRs.

In this thesis, we formulate the visibility-based technique to study the statistics of the CNM phase of the ISM, probe the magnetohydrodynamic turbulence in the SNR, and study the large scale structure of CNM toward SNR Tycho with the help of the similarity index method. We arrange the thesis in the following manner. Chapter 1 reads the basic introduction followed by the radio interferometry in chapter 2. We describe the magnetohydrodynamic turbulence in SNR Cassiopeia-A in chapter 3, and chapter 4 discusses the statistics of the CNM phase of Galaxy with the analytical method. Chapter 5 presents the CNM structure toward the Tycho supernova, and the conclusion of the thesis is presented in chapter 6.