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It is certified that the work contained in the thesis titled **Mapping Structures in the Galactic Cold Neutral Medium and Supernovae Remnants** by **Mr. Pavan Kumar Vishwakarma** has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. degree.

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I, **Pavan Kumar Vishwakarma**, certify that the work embodied in this thesis is my own bona-fide work and carried out by me under the supervision of *Dr. Prasun Dutta* from July 2015 to December 2020 at the *Department of Physics*, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers whenever and wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any others' work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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Place : IIT BHU, Varanasi Pavan Kumar Vishwakarma

CERTIFICATE BY THE SUPERVISOR(S)

It is certified that the above statement made by the student is correct to the best of my knowledge.

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Dedicated to

My Parents, family and all my friends . . . .

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Pavan Kumar Vishwakarma

Abstract

In this thesis, we study the statistics of the H I column density in the cold neutral medium (CNM) of the interstellar medium (ISM) from absorption studies, magnetohydrodynamic turbulence in the supernova remnants (SNRs) Cassiopeia-A and H I absorptions towards the Tycho's supernova remnants using the radio-interferometric observations. We analytically study how radio-interferometric observations can be used to measure the two-point statistics of the optical depth fluctuations. Studies related to the scale-invariant structures in the CNM of a galaxy constrain the density structures. We investigated how the physical properties of the CNM, related to the spin temperature and column density can be studied using the H I absorption studies against extended background sources. We present our methodology and calculations using some fiducial values of the physical parameters of the ISM. Our study shows that whatever thermal properties of the CNM clouds would be, we can estimate the scale-invariant structures of the H I column density using the absorption studies. However, it alone would not be sufficient to trace much about the amplitudes of the spin temperature and column density fluctuations and requires multiwavelength observations for such a study. We proposed a particular model of the anisotropic power spectrum that counts the effect of the anisotropic fluctuations in H I, on the isotropic power spectrum of H I. Our model of the anisotropic power spectrum scales such that, in the case of extreme anisotropy, the maximum modification in the amplitude of the isotropic power spectrum would be just half. We also concluded that even though the spin temperature and H I column density in the ISM are completely uncorrelated, partially correlated or completely correlated, they all have a similar effect on the statistics of the optical depth fluctuations. Our analytical study combined with measurements of the H I optical depth power spectrum in different directions of the Galaxy can solve the long-standing puzzle that, if there is a singular turbulence cascade present in the ISM

producing the scale-invariant structures from mpc to pc length scale?, or it is only due to the fact that we have only few measurements of the H I column density power spectrum in different directions of our galaxy? Our analytical study has clarified that to measure the slope of the H I column density power spectrum in the CNM of galaxies; we can directly use the slope of the optical depth power spectrum. This analytical study is important since, at the small scales, determination of the H I column density power spectrum is directly not accessible as at smaller scales detection of H I column density through emission is relatively difficult. In this thesis, we also use the radio-interferometric observations to study the magnetohydrodynamic turbulence in the supernova remnants Cassiopeia-A. We use the recently developed unbiased method to calculate the magnetic field disturbances in the vicinity of supernova remnants Cassiopeia-A shocks, using the autocorrelation of the synchrotron intensities. We found that the magnetic energy spectra in the vicinity of SNR Cassiopeia-A shocks are of trans-Alfvenic nature i.e., follow the 2/3 power law. Such statistics were predicted theoretically decades ago but were not explored much in the observations. We numerically verified our results using the theoretical predictions for the trans-Alfvenic magnetohydrodynamic turbulence. Our results of the magnetic energy spectrum can be explained with the help of the magnetic field amplification in the vicinity of SNR shocks. On the global scale, it is found that MHD conditions in the proximity of the shocks are compatible with the Alfven Mach number of unity. The radial window of the magnetic field amplification in the proximity of the shocks is found to be ~ 0.11 pc. Young supernovae remnants like Cassiopeia-A are observed with two shocks, a forward shock, and a reverse shock. Our results predict the existence of a subshock in the SNR Cassiopeia-A along with forward and reverse shocks in the SNR Cassiopeia-A. In this SNR, we found that the radial window of the MHD turbulence present in the proximity of the shocks spans over the angular width of 7". Almost similar angular width is calculated from the theoretical predictions under the regime of the advective and convective flow of the particles in the proximity of the young SNR shocks. Our measured values of the power-law index are 2/3 within the uncertainty of 2 sigma and show that the trans-Alfvenic MHD is almost achieved in the vicinity of this SNR. We also found that the location of our predicted subshock in the radio frequency observation matches the location of the reverse shock measured in the X-ray observations. We suggest that reverse shock in the X-ray observation must affect the electrons responsible for the synchrotron emission in the radio frequency observations from the background to produce the fluctuations being reflected in our statistics. Such findings are important to test the validity of the theoretical predictions of the MHD turbulence and diffusive phenomenon in the vicinity of the SNR shocks. We calculate the Alfven-Mach number by using the surveys of the number density of ions and electrons as well as the amplified magnetic field in this SNR. Our calculations show that the range of the Alfven Mach number, which is effective in this SNR at this stage, is 1.3-3.3, which is almost capable of producing the trans-Alfvenic like MHD condition. Theoretically, the value of the amplified magnetic field is found to be responsible for such a large value of the Alfven Mach number in the vicinity of the shocks. Using our results and theoretical predictions, we investigated that if such SNRs will be capable of accelerating the Cosmic-Rays up to a very high energy limit ($\sim$ PeV), under the Quasilinear theory of turbulence as studied numerically. By combining our results and the measured energy of the Cosmic-Rays in this SNR, we found that such SNRs would not be capable of accelerating Cosmic-Rays with energy larger than the TeV order, at least at the present stage. On the one side, where our results of the found trans-Alfvenic MHD turbulence in the SNR Cassiopeia-A validated many theoretical predictions made about it, at the same time, it also rejects other theoretical predictions that claimed that high energy Cosmic-Rays in the Galactic ISM might be sourced from these young SNRs. We will carry out such more measurements in the near future. This is required to fully understand the nature of magnetic field disturbances in the SNR and testify the more theoretical predictions about

MHD turbulence in the SNRs. Finally, using the radio-interferometric observations toward another Galactic SNR, called Tycho's SNR, we also carry out the H I absorption studies towards it and a point source close to its line of sight. We study the H I absorption features across the face of Tycho's SNR and point source to analyze the H I cloud distributions in these directions. We also studied the correlation between the optical depth spectra of point source and Tycho's SNR using the similarity index method and Spearman's rank correlation method. Our study found that the velocity range of the absorption found in the direction of Tycho's SNR, produced by the Local arm, is much wider than other nearby Galactic supernovae remnants, and it spans a wide range of -23.73 to 10 km/s in the LSR velocity. Such an observation is opposite to what is earlier observed in the direction of nearby SNR Cassiopeia-A. The absorption seen in the direction of the point source shows more absorption windows than seen in Tycho's SNR direction. The maximum absorption seen in the direction of Tycho's SNR is at -48.55 km/s while it is at -60.66km/s in the direction of the point source. We use the most accurate distance of the companion of the Tycho's SNR to find the excess velocity observed in the direction of these sources. The distance of the absorption produced at -60.66 km/s in the direction of the point source is found to be $\sim$ 2.9 kpc. These studies reveal that there is inhomogeneity in the H I cloud distribution in the direction of the eastern and western edge of Tycho's SNR at LSR velocity of $\sim$ -48.5 km/s. We found that the H I absorption spectra in these directions have an excess velocity of $\sim$ -23 km/s. We propose a model of the extended cloud that could explain the observed absorptions towards the Tycho's SNR and point source. Based on our calculations, we show that the length of the associated cloud must extend beyond one kpc. We also reveal that the location of Tycho's SNR is not favorable in the depth of H I clouds in Perseus arm, but it must be somewhere behind the Local arm and at the near edge of the Perseus arm. Such studies are essential to understand the environment around young SNRs and its effects on their evolutions. This study can be used to map the spin temperature and

H I distribution in the CNM phase of the ISM around Tycho's SNR.

Key words : Interstellar Medium (ISM), Turbulence, MHD, Auto-correlation Function, Shock Waves.

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