

CERTIFICATE

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.

Prasun Dutta

16/12/2020

Signature: Supervisor

Dr. Prasun Dutta

Department of Physics

IIT (BHU)

Varanasi

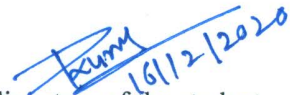
Assistant Professor,
Department of Physics
Indian Institute of Technology
(Banaras Hindu University)
Varanasi-221005

DECLARATION BY THE CANDIDATE

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.

Date : 16/12/2020


Place : IIT BHU, Varanasi



Signature of the student

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.


Supervisor : ~~Assistant Professor~~
Dr. Prasun Dutta **Department of Physics**
Department of Physics **Indian Institute of Technology**
(Banaras Hindu University)
Varanasi-221005
IIT (BHU)
Varanasi


Signature of Head of Department/Coordinator of School
HEAD/विभागाध्यक्ष
भौतिकी विभाग/Dept. of Physics
भा०पी०सं०/(का०हि०वि०)/IIT (BHU)
वाराणसी/Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis : Mapping Structures in the Galactic Cold Neutral Medium and Supernovae Remnants.

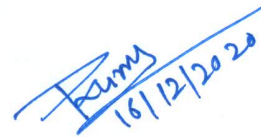
Name of the Student : Pavan Kumar Vishwakarma

Copyright Transfer

The undersigned hereby assigns to the Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the Ph.D. degree.

Date : 16/12/2020

Place : IIT BHU, Varanasi



Signature of the student

Pavan Kumar Vishwakarma

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

Dedicated to

My Parents, family and all my friends . . .

Acknowledgements

I am very much thankful to my supervisor Dr. Prasun Dutta for helping me at every step here. I will always remain grateful for his excellent academic guidance during my Ph.D. work. I would also like to thank my family, all the teachers of the department, RPEC members, and everyone from the institute who could help me directly or indirectly during my Ph. D. days in this department. I am very much thankful to the Government of India for providing me GATE fellowship during my Ph.D. I am also grateful to Nirupam Roy (IISc Bangalore) for discussions during my Ph.D. I want to thank all my today's/previous labmates of the radio-astronomy group i.e. Nandini Sahu, Vivek Gupta, Jais Kumar, Meera, and Urvashi. They all have been very supportive, and it has been an opportunity for me to learn and work with them. It always has been a very positive response from the side of Vivek Gupta and Aditya Chaudhary (NCRA). They have significantly helped me to understand the many fundamental concepts and tools required for me as a beginner. My batchmates Dibyojyoti Mohanta, Dharmendra, Ashish, Vijay, Vinod, Prajyoti, Ruchi, Ritika, Chinmoy, and Sadique, you all always supported me here at every moment. You all will remain special friends to me. All the astronomy students Sudheer, Balveer, Sanjeet, Pawan, Menon, Soumyadeep, Rajat, Archisha, and Yamini, always have created a festive atmosphere to learn astronomy here. I am also thankful to all other my friends in the institute i.e. Harshit (IMD), Utkarsh (IMD), Abhijit(IMD), Ajay Kumar, Manish, Jai Praksh (J.P.), Vivek, Abhishek, Digvijay, Rohit Shukla, Ramani, P.K. Pande, Sachin, Anuvrat, Harsh, Kanchan, Ravi, Pawan Mishra, Pragati Singh, Vaibhav, Kuldeep, Vipin, and all others. I am also thankful to my two juniors Mahima and Vandana, who have helped me here from time to time.

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-Alfvénic 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-Alfvénic 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 Alfvén 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 -60.66 km/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 ~ 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 ~ -48.5 km/s. We found that the H I absorption spectra in these directions have an excess velocity of ~ -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.

Table of contents

List of figures	xv
List of tables	xx
1 Introduction	1
1.1 Introduction	1
1.2 The Interstellar Medium (ISM)	3
1.3 Probing the ISM	5
1.4 Turbulence in the ISM	7
1.5 This Thesis	11
2 Techniques of Radio Interferometry	15
2.1 Introduction	15
2.2 Radio Interferometers	16
2.3 Data analysis methodologies	22
3 Trans-Alfvenic magnetohydrodynamic turbulence in the vicinity of supernova remnant Cassiopeia-A shocks	31
3.1 Introduction	31
3.2 Method	33
3.3 Analysis	34

3.4	Results	39
3.5	Discussion	40
4	H I Column Density Statistics of the Cold Neutral Medium from Absorption Studies	44
4.1	Introduction	44
4.2	Two point statistics of the optical depth from observed visibilities	46
4.2.1	Specific intensity of 21-cm radiation	46
4.2.2	Autocorrelation function of optical depth fluctuations	47
4.2.3	Measuring the optical depth autocorrelation from radio-interferometric observations	48
4.3	Relation of optical depth autocorrelation with statistics of the H I column density and spin temperature	49
4.4	Sensitivity of observables on the physical parameters	52
4.4.1	With isotropic column density fluctuations	52
4.4.2	Effect of anisotropic fluctuations	54
4.5	Discussion and Conclusion	57
5	H I absorption towards the Tycho's supernova remnant.	60
5.1	Tycho's Supernova remnant	61
5.2	Observation and Data Analysis	63
5.3	Spectral Analysis and Result	66
5.4	Discussion and Conclusion	75
6	Conclusions and Future Scope	78
	References	81

Table of contents	xxi
-------------------	------------

Appendix A	93
-------------------	-----------

A.1	93
---------------	----

List of figures

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.)	13
2.1	: Image shows the GMRT antenna positions, taken from Swarup et al. (1991). The dot points inside the zoomed circle are the central part of the GMRT consisting 14 antennas.	20
2.2	: The above figure shows the observation strategy of a target source along with calibrators. Flux Calibrators (FC1 and FC2) and Bandpass Calibrators (BP1 and BP2) are observed at the beginning and end, while Phase Calibrator (PC) and Target source (TS) are observed alternatively. .	24

3.1	: Continuum image of the Cas-A. Here central dot point shows the center of the SNR. The innermost and outermost circles define the region in which the correlation function is measured. The three inner consecutive black circles with mean radii at $0.633R$, $0.780R$ and $1.000R$ define the positions of the shocks and subshock in the SNR in terms of the radius R of the supernova. The exact range defining the three regions are given in table 3.1.	36
3.2	: Spectra of region 1 (upper panel) and region 2 (lower panel). For comparison we have plotted $2/3$ law point to point.	37
3.3	: One of the best chosen spectra from region 1 (upper panel) and region 2 (lower panel) as shown in figure 3.2.	37
3.4	: Spectra of region 3 showing the compatibility with $2/3$ law near to the forward shock position.	38
3.5	: One of the best chosen spectra from region 3 (see figure 3.4).	38
4.1	: Variation of optical depth auto-correlation function $\xi_\tau(\theta)$ as a function of θ for different values of α_{HI} . Here γ , η and σ_{HI} are taken 0, 0.5 and 0.1 respectively.	50
4.2	: Variation of $\Xi(\vec{U})$ with baselines (U) is shown for different values of the parameters α_{HI} , σ_{HI} , η and γ . In each panel, one of the parameters is varied, keeping the other fixed (see section 4 of this chapter).	53
4.3	: Variation of Φ as a function of azimuthal angle ϕ in the baseline plane for different values of the anisotropy parameter f_a	56
4.4	: Variation of \mathcal{R} with anisotropy parameter f_a . The asymptotic value of \mathcal{R} (0.5) is represented by dashed gray line.	56

- 5.1 : a) Continuum image of the Tycho's SNR along with point source at 00:29:45.475, +63.58.40.727 (J2000) (inside circle) made using the baseline range 0-25K λ . Since in our image only this point source is visible, so we will call it the point source at all references for it, b) Low resolution (0-5K λ) continuum image of Tycho's SNR. The numbers given in the horizontal and vertical axes in images correspond to pixels. For the 0-25K λ image each pixel has a dimension of 4arcsec \times 4arcsec. For 0-5K λ , the pixel size is 8.0arcsec \times 8.0arcsec. 66
- 5.2 : Figure shows the six optical depth images averaged in the velocity ranges, as shown in the labels. These images are made using the baseline range of 0-5K λ . Optical depth images made by averaging in LSR velocity ranges from -25.85 km/s to -33.57 km/s, -23.28 km/s to -16.84 km/s, -16.84 km/s to -09.08 km/s, -09.08km/s to -00.08km/s and -00.08km/s to 08.94 km/s show significant absorptions at the overall face of Tycho's SNR, while in the range -45.20 km/s to -51.63 km/s, it shows higher absorption toward the eastern edge. The quantity shown in the image is optical depth and bar at the bottom of the image shows its magnitude. 67

- 5.3 : Optical depth spectra (with 1σ error bars) of H I absorption towards point source (PS) and Tycho's SNR in the baseline range $1.3-40K\lambda$ are shown as upper panels in the above figures. H I emission profiles, taken from LAB survey (Kalberla et al., 2005) in their directions with velocity resolution of 1.30 km/s are shown as lower panels. The typical per channel sensitivity in brightness temperature for the LAB survey is $\sim 0.1 \text{ K}$. Vertical lines, marked as I, II, III, IV and V in these spectra show velocities 0.59 km/s , -15.84 km/s , -26.48 km/s , -51.62 km/s and -62.25 km/s and are made in reference to the maximum absorptions in the direction of point source in the windows of its absorption as mentioned in the text. 68
- 5.4 : Left: Comparisons of the optical depth spectra of point source with two optical depth spectra toward the left and right face of Tycho's SNR. Right: Four spectra of optical depth toward the left region of Tycho's SNR. The velocity resolution of the spectra is 1 km/s . The marked vertical lines refers to the velocities as shown in figure 5.3. 70
- 5.5 : Optical depth spectra for different regions along with spectra of point source (PS) are shown. The figure helps to easily compare the spectra correlated with each other. 72
- 5.6 : Similarity index and Spearman's rank (S R) correlation between the spectra of the point source (reg 0) and four different regions (reg8, reg 9, reg13 and reg18) of Tycho's SNR. Vertical lines represents the marked velocities as shown in figure 5.3 73

5.7	: Approximate location of Tycho’s SNR (red dot) in our Galaxy and geometry to calculate the excess velocity of cloud in the direction of the point source. The left figure is taken from <i>Annu.Rev.Astron.Astrophys</i> (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 <i>Astronomical Society of the Pacific</i> (Copyright 2009,Astron.Soc.Pac.)	74
A.1	: The figure shows the modified version of figure 3.2. We have relatively scaled the amplitudes to clarify the differences in the spectra.	94
A.2	: Similar to the figure A.1, this figure also show the modified version of the figure 3.4. Amplitudes are scaled for the purpose of visualization. . .	94
A.3	: Normalized statistics of the magnetic field disturbances from the radial region of 0.526R to 0.820R.	95
A.4	: The figure shows the normalized magnetic energy spectra from the radial region of 0.826R to 1.093R	96

List of tables

3.1	The position and width information about the different regions of the supernova used in the analysis.	36
3.2	Fitted values of α for the spectra shown in figures 3.2 and 3.4.	39
4.1	Different auto-correlation functions and the corresponding power spectrum of the observables used in this chapter.	46
5.1	Various distance estimates of Tycho's SNR from different references.	62
5.2	Observation summary for GWB and GSB.	64
5.3	Details of the calibrators for this observation.	65