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Motivation and Objective

Questions I know the answers to I don't need to ask, right?

—Calvin

The interstellar space in galaxies is filled with the gas containing hydrogen, helium, carbon, calcium and other elements, as well as dust grains. This is known as the **interstellar medium** (ISM). In addition, fast moving charged particles (cosmic rays) and magnetic fields also permeate the interstellar space. The ISM is observed to be highly inhomogeneous with most of the mass being concentrated in clouds, both atomic and molecular, which, however, occupy a small fraction of the volume of the Galaxy. The rest of the volume is filled by a warmer all pervading intercloud gas.

This thesis primarily deals with the kinematics of the diffuse atomic interstellar clouds. We have carried out observational studies of the interstellar medium using the 21cm-line of atomic hydrogen (HI). The Galaxy's ISM is generally transparent (optically thin) at the 21cm line frequency, and hence the HI observations can be used to probe the ISM well beyond the optical horizon. Observations of the HI 21cm-line provide information on a broad range of physical properties of the ISM.

1.1 MOTIVATION

One of the first efforts to study the nature of the ISM was the observation of Interstellar absorption in the optical line of singly ionized calcium (CaII) towards early type stars by Adams in 1949. This study revealed the presence of absorption lines at various velocities in each line of sight. After the discovery of the 21cm line, extensive observations lead to our present understanding of the ISM, with cool diffuse Interstellar clouds in pressure equilibrium with a rarer and warmer Intercloud medium. However, the velocity distribution of Interstellar clouds as seen in the optical lines and the 21cm line were found to be different. The optical absorption line studies always indicated the presence of a larger velocity fraction, which was absent in the 21cm line observations. This is clear from Fig. 1.1

In a recent Ph.D. thesis by Rajagopal (1997), a direct comparison of Interstellar absorption features seen in optical lines to the HI 21cm line was attempted. The idea is to identify those lines of sight where a star whose spectra is known to contain Interstellar optical absorption lines at different velocities and a radio source aligned close to the star (Fig. 1.2). This was the first time that such a study was carried out. These observations were carried out using the Very Large Array (VLA) and had a detection limit $\gtrsim 0.1$ in HI optical depth.

The main advantage of the absorption measurement is that it provides higher angular resolution. Earlier studies where attempts were made to measure HI emission towards stars invited one major criticism: the beam sizes of the single dish radio telescopes used for these studies were $\sim 30'$. Comparison of features detected at such an angular resolution with those from the arc second resolution achieved in optical absorption studies is difficult. The higher velocity features might be missing in HI emission due to beam dilution. Another important aspect of an absorption experi-

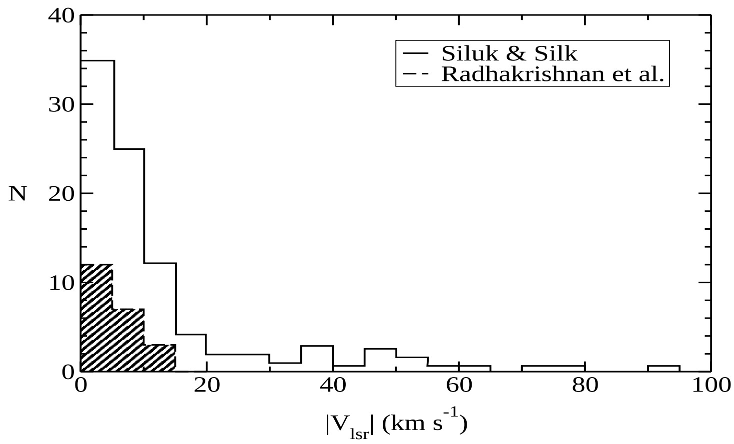

Fig. 1.1 The histogram of radial velocities derived from the optical absorption line studies by Siluk & Silk (1974), along with that from the HI absorption line survey by Radhakrishnan et al., 1972 (dashed line). The higher velocity tail is missing in the radio observations.

ment is that, in combination with existing HI emission data, the spin temperature of the absorbing gas can be calculated. An estimate of spin temperature is important, since this would help in establishing the correspondence between the clouds identified through optical absorption lines and those seen in the radio.

Rajagopal (1997) studied twenty four fields where a star and a radio source was aligned along the same line of sight. Figure 1.3 shows one sample HI optical depth profile from Rajagopal (1997). The velocities of the optical absorption lines are marked by vertical arrows. In most cases, it was found that the velocity of the HI absorption features agreed with the optical absorption line at low velocities ($|v| \lesssim 10$ km s^{-1}). It was also found to match with the discrete features identified from existing HI emission line profiles. The derived spin temperature and line widths suggested that the low velocity optical absorption lines are arising in the general population of cold diffuse clouds in the ISM. However, none of the higher velocity features seen in optical absorption lines were detected in HI absorption. Recall that the earlier HI emission surveys had also failed to detect HI corresponding to the optical absorption lines at higher velocities.

These non-detections prompted them to advance a scenario which supports the hypothesis that the high velocity optical absorption lines arise in Interstellar clouds, shocked and accelerated by supernova remnants in their late phases of evolution. Such a mechanism would naturally result in the higher velocity clouds being warmer and also of lesser column density as compared to the low velocity clouds, due to shock

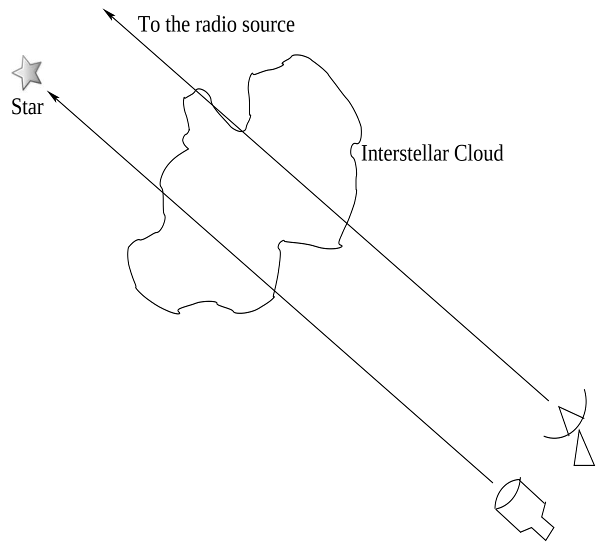

Fig. 1.2 Comparison of optical and radio absorption lines arising in the Interstellar clouds

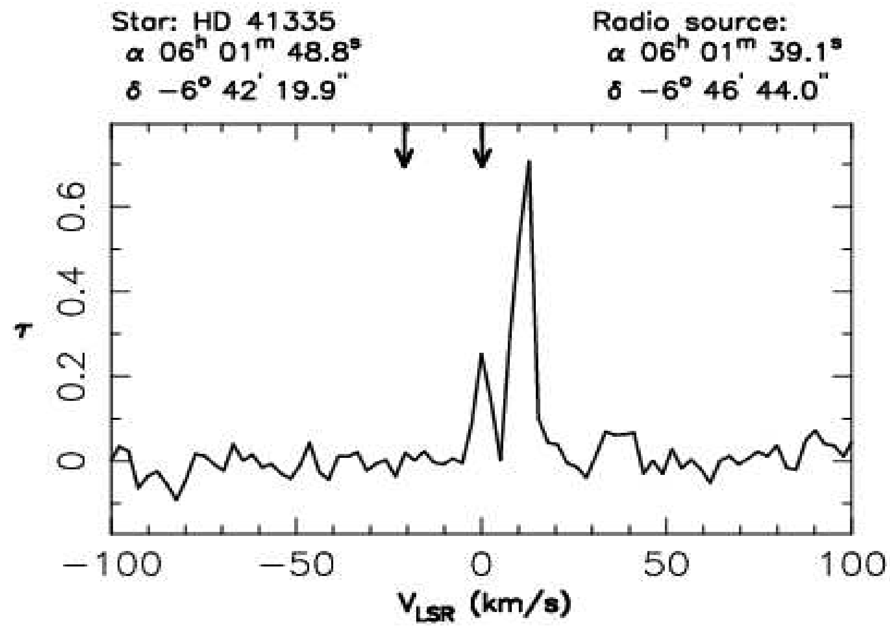

Fig. 1.3 One of the 24 fields investigated by Rajagopal (1997). The HI optical depth profile is shown, along with the velocity of the optical absorption lines marked by arrows along the velocity axis. The low velocity optical absorption line (near v $\sim$ 0 km s^{-1}) is detected in HI absorption, but, the higher velocity optical line has no corresponding HI absorption.

heating and acceleration. Apart from this, the shock may result in cloud fragmentation, resulting in smaller sizes for the higher velocity clouds.

1. If the above mentioned scenario is correct, deeper, more sensitive HI absorption measurements should be able to detect the higher velocity clouds. There is enough room to improve upon the existing observations. *One can look for directions where the star and a brighter radio continuum source are aligned closer. Longer observations would help to go deeper in sensitivity*.

2. In addition to looking for HI absorption from the very same clouds seen in optical absorption, one can try to derive an independent distribution of radial velocities of interstellar clouds by doing a deep HI absorption survey towards bright radio continuum sources. In order to build sufficient statistics of HI absorption features and compare it with the existing optical data, one will need higher sensitivity levels (assuming the conjecture of shock heating to be true) and also a survey at higher Galactic latitudes where the lines of sight sample roughly the same clouds as seen towards bright stars. The recently completed Giant Meterwave Radio Telescope, which consists of 30 dishes of 45 meter diameter, is ideal for such an experiment. Its excellent collecting area would help to achieve deep sensitivity limits in reasonable integration time.

3. As we mentioned earlier, previous radio observations in the 21cm line towards the stars failed to detect the higher velocity clouds in HI emission as well as absorption. However, there exist some evidence for the presence of a population of fast clouds from radio studies in the 21cm line. Towards the Galactic center and the anticenter the radial component of differential Galactic rotation is minimum. An HI line study along these two lines of sight, therefore directly provide information about peculiar velocity distribution of Interstellar clouds. HI absorption study towards the Galactic center was carried out about 30 years ago (Radhakrishnan et al., 1972). The results from this investigation suggested the existence of two populations of Interstellar clouds, one of them with low velocity dispersion ($\sigma_v \sim 5$ km s^{-1}) and another with a much larger velocity dispersion ($\sigma_v \sim 35$ km s^{-1}; Radhakrishnan and Sarma, 1980). However, later attempts to verify this result found no evidence for such a wide component. This has remained controversial since then and need to be verified. There has been no HI absorption study towards Galactic anticenter, which will provide vital information to shed light into the existing controversies.

4. According to the widely accepted model of the interstellar medium, cool diffuse HI clouds exist in pressure equilibrium in a warmer intercloud medium (or the Warm Neutral Medium, WNM), as shown in Fig. 1.4. Of the two phases in the ISM, the intercloud medium remains the least well understood. Although HI emission from the WNM is detected easily in almost every direction in the sky, measuring HI absorption from the WNM is difficult due to its higher temperature ($\tau_{HI} \propto N_{HI}/T_S$). Only two measurements of HI optical

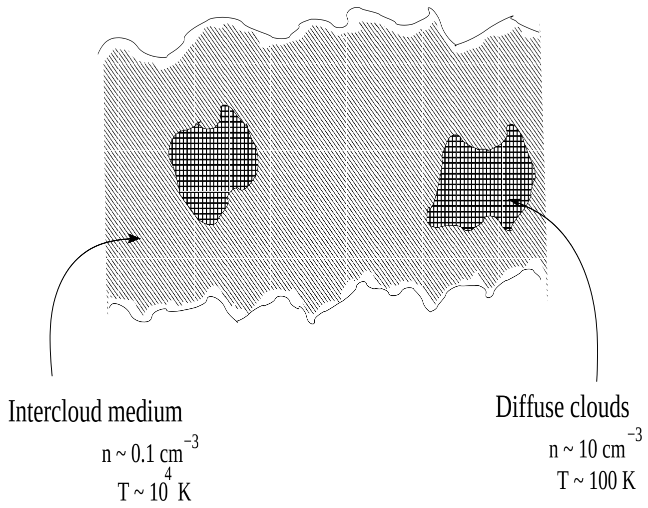

Fig. 1.4 The two phases of the ISM: cold diffuse clouds in pressure equilibrium with a warmer intercloud medium. This cartoon does not show the more dense molecular clouds.

depth of the WNM exist and those are very recent. Absorption measurements towards several directions in the Galaxy will result in a more accurate, global estimate for the optical depth and thereby spin temperature of the WNM. The spin temperature of the WNM is an important parameter with implications for models of the Interstellar medium. To verify the predictions of various theoretical models, one need to have an estimate of the temperature of the gas, which is lacking.

The motivation of the investigations reported in this thesis are the four points mentioned above.

1.2 OBJECTIVE

One possible explanation for the non detections of HI absorption in the higher velocity clouds seen in optical absorption lines, by Rajagopal (1997) is that these clouds are having smaller dimensions, in which case, unless the line of sight to the star and that towards the radio source are not aligned close enough, they will sample different gas. Although shock acceleration of clouds seemed to provide satisfactory explanation for the non detections of HI absorption from the higher velocity clouds, to strengthen that hypothesis it is important to observationally establish a correlation between the 21cm optical depth and the peculiar velocity. As a part of a continuing effort towards this end, we have selected a list of directions where a radio continuum source is aligned close to an early type star, towards which optical absorption line study has been carried out already. We have selected directions where the alignment of the star and the radio source is much closer than in the observations by Rajagopal et al. *In our source list, the linear separation between the two lines of sight (towards the radio source and towards the star) are less than 1 pc at half the distance to the star*. **We used the GMRT to measure HI absorption along these lines of sight and reached a limit on the optical depth ten times better than that achieved by Rajagopal (1997)**.

To derive the peculiar velocity distribution of interstellar clouds using the 21cm line, **we selected 104 bright (S$_{20cm} > $ 1Jy) radio continuum sources distributed at high Galactic latitudes $|b| > $ 15°**. We used the GMRT to measure HI absorption towards these sources, **with an rms optical depth sensitivity $\sim$0.003**. That makes it the most sensitive HI absorption survey carried out so far. Though the main aim of this study is to analyze the peculiar velocity distribution of interstellar clouds, this data is useful in addressing a variety of other interesting issues related to the physical properties of neutral hydrogen in the interstellar medium.

To resolve the controversy regarding the Galactic center observations (Radhakrishnan and Sarma, 1980), **we have imaged the Galactic Center region using the Australia Telescope Compact Array (ATCA)**. A good spectral baseline and a stable bandpass are crucial to search for a wide and shallow absorption feature. In addition, a high spectral resolution is needed to fit and subtract the narrow HI absorption lines. The ATCA is the most appropriate instrument for such an experiment. In addition to this, **we have measured HI absorption towards two radio continuum sources within half a degree from the Galactic anticenter, using the Westerbork Synthesis Radio Telescope (WSRT)**. These observations would provide important information that would shed light on this longstanding and controversial issue.

As we mentioned earlier, the Intercloud medium remains the least understood of the two phases in the ISM. Only two measurements of HI absorption in the WNM exists. What is required now is a search for WNM absorption at moderate latitudes and towards lines of sight that sample a range of Galactic longitudes. This set of observations will be a powerful tool in exploring the possible variations in the properties of the WNM. These observations require a very high spectral dynamic range, because here the search is for an absorption with optical depth of $\sim 10^{-3}$ among the deep, often optically thick features arising from the cold clouds. Spectral dynamic range of 1 part in 7,500 or better is required and the only instrument which can provide bandpass stability to reach these levels in reasonable integration time is the Westerbork Synthesis Radio Telescope. Hence, we have used the WSRT to search for HI absorption in the WNM towards five radio continuum sources. The selection criteria was that the Galactic latitude of the source should be less than $\sim 15^o$ and the 20cm flux density > 5Jy and the sources should be at an observable declination for the WSRT. An additional criterion was the number of spectral features arising from the CNM should be minimum. The HI emission profile toward each of these 5 sources (From the Leiden-Dwingeloo Survey of Galactic neutral hydrogen) shows less than 8 narrow components. The wide HI emission feature arising from the WNM is prominent in all these directions, with a mean value, $T_B \sim 6.0$ K.

1.3 OUTLINE OF THE THESIS

Chapter 2: In this chapter we describe deep Giant Meterwave Radio Telescope (GMRT) HI absorption observations toward radio sources located at small angular separation from bright O and B stars whose spectra reveal the presence of intervening high random velocity CaII absorbing clouds. There were several attempts to compare the features seen in the optical spectrum to the HI emission features along the same line of sight. These efforts have revealed serious discrepancies. The optical estimates of the number of clouds per kpc has always tended to be higher than the radio (HI) estimates. The velocity distribution shows a high velocity tail in the optical, not seen in HI observations. The questions that are addressed in this chapter are:

- What is the nature of the gas which give rise to the larger velocity optical absorption lines?
- Compared to the standard Interstellar clouds identified in HI studies, are they warmer or their HI column density is lower?

Our observations are basically an improvement over the existing studies in this regard (Rajagopal, 1997).

Chapter 3: In this chapter we discuss the high Galactic latitude HI absorption survey using the GMRT. The radial velocity distributions of interstellar clouds derived from optical and radio observations are inconsistent with one another. The high velocity tail of the cloud population appears to be absent in the radio surveys. The previous chapter is about the direct comparison of Interstellar radio and optical absorption spectra. To achieve very high sensitivity in HI optical depth one needs a very bright radio continuum source aligned along the same line of sight as a star. Such a close alignment is not feasible. Keeping in mind the explanations for large velocities by Siluk & Silk (1974) as originating in the SNRs and the conjecture by Rajagopal, 1997, one can expect these higher velocity clouds to have less column density as compared to the lower velocity clouds (due to shock heating and evaporation). Hence, we have decided to build statistics for deep HI absorption spectra independently, and to search for the higher peculiar velocity HI absorption features. The existing interferometric HI absorption surveys are all sensitive only to an extent of detecting optical depth $\gtrsim 0.05$. Our observations are at least a factor of 5 more sensitive than the existing surveys. This chapter attempts to answer the following questions:

- What is the true distribution of peculiar velocities of Interstellar clouds?
- Does the higher velocity optical absorption line features represent a distinct, separate population?
- If they do, then where do they fit in our picture of the ISM?
- If they do not, then what is the reason behind their larger velocities?

In addition to the primary motivation, this data is also useful to address a variety of interesting problems related to the physical properties of neutral atomic gas in the ISM.

Chapter 4: This chapter is an attempt to solve an important, and at the same time, ignored controversy. An HI absorption study towards the Galactic center had suggested evidence for a separate population of Interstellar clouds with larger velocity dispersion as compared to the well known cold diffuse clouds. However, later observations to verify this claim gave negative results. This chapter describes our observations using the ATCA and the WSRT, HI absorption study towards the Galactic center and Galactic anticenter, respectively. We have addressed the following questions:

- Is there any evidence for a wide HI absorption line towards the Galactic center, which was supposed to indicate the presence of a global population of large velocity interstellar clouds?
- If yes, then how can one explain the results of those studies wherein no such line was detected?
- If there exists such a wide line, then is it arising from a global population of Interstellar clouds or is there any other possibilities?

Chapter 5: In this chapter we discuss a search for HI absorption in the Intercloud medium. Only two measurements of HI optical depth of the intercloud medium exist. Absorption measurements towards several directions is needed for a more accurate, global estimate for the optical depth and thereby spin temperature of the gas that constitute the intercloud medium. The spin temperature of this gas is an important parameter with implications for models of the Interstellar medium. To verify the predictions of various theoretical models, one need to have an estimate of temperature of the gas. This brings us to the basic motivation behind our observations using the WSRT, discussed here.

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