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WHAT HAVE WE LEARNED ABOUT THE INTERSTELLAR MEDIUM FROM PULSAR RADIO SPECTROSCOPY?

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Abstract. Several applications of pulsar radio spectroscopy have provided important and unique contributions to studies of the interstellar medium (ISM). Pulsar observations of the cold, diffuse ISM probe the extreme (AU-scale) end of the turbulent spectrum suggesting the prevalence of the incompressible type of fluctuations. Pulsar observations of the hydroxyl molecule clearly demonstrate significant clumpiness of molecular clouds. The exciting detection of the pulsar-stimulated emission at 1720 MHz represents direct and unique evidence for an interstellar maser in action. This stimulated emission cycles with the pulsar's pulse on millisecond timescales and represents the quickest variations ever observed in any interstellar maser.

1. INTRODUCTION

For many years there have been theoretical and observational support for structures in the interstellar medium (ISM) on scales $\gtrsim$ 1 pc (Dickey and Lockman, 1990). These studies have shown a variety of atomic hydrogen (HI) features, while statistical studies have revealed a power-law behavior of the spatial power spectrum for the HI emission fluctuations in the Galaxy (Crovisier and Dickey, 1983; Green, 1993), and more recently in several nearby galaxies (Stanimirovic et al., 1999; Elmegreen, Kim and Staveley-Smith, 2001). While this power spectrum suggests that there are no preferred spatial scales in the diffuse ISM, the roles individual scales play in the general ISM can be distinctly different. The largest spatial scales govern galactic rotation, for example, while at intermediate scales numerous examples of energy injection can be found (e.g. stellar winds, expanding shells, chimneys etc.). However, not much is known about the structure in the diffuse ISM on extremely small spatial scales, of order of a few tens of astronomical unit (AU), and its importance in the ISM. This is partially due to instrumental limitations as current radio telescopes can not directly image structure on AU-scales at cm wavelengths. However, a few indirect observational techniques exist to reach those extremely small spatial scales. One of them is based on radio-spectroscopic observations of pulsars.

Studies of the absorption of pulsars' signals by the intervening medium have been a very powerful way for studying the properties of the ISM. Pulsars' continuum emission subtends an extremely small solid angle, allowing us to probe needle-thin samples of the ISM. More importantly, some pulsars have large transverse velocities (typically 5–50 AU/year), allowing for searches of the variability of HI absorption spectra, which, if present, signify density irregularities on scales traversed by the pulsar. Another important characteristic that makes pulsars particularly suitable as background sources is their pulsed radiation, which allows us to investigate, in both emission and absorption, *almost exactly the same line-of-sight* (Weisberg et al., 1995).

The most traditional application of the pulsar radio spectroscopy is for measuring pulsar kinematic distances and the electron density distribution of the Galaxy. The use of pulsar HI absorption spectra for studies of the small-scale structure has been implemented in early 90s (Deshpande et al., 1992; Frail et al., 1994). A more recent application of pulsar spectroscopy, that started with Stanimirovic et al. (2003), uses OH absorption spectra towards pulsars to study properties of the molecular medium. This application led to the recent detection of the pulsar-stimulated maser emission at 1720 MHz (Weisberg et al., 2005), which is providing important insights into the maser emission mechanism.

In this paper we present results from several applications and emphasize their contributions for our understanding of general properties of the ISM. In Section 2 we summarize a typical observing strategy. Section 3 focuses on the electron density distribution in the Galaxy, while Section 4 discusses recent results from the pulsar studies of the AU-scale structure in the cold, atomic medium. In Section 6 we address the pulsar approaches for studying internal structure of molecular clouds, and we conclude in Section 7.

2. OBSERVING STRATEGY

Pulsar radio spectroscopy requires a fast-sampling backend which can record spectra, in either the raw (complex voltage) or the Fourier-transformed form, on short timescales. The final data output, after the correction for the frequency dependent time delay, is a data cube of spectra as a function of time. The 'pulsar-on' and 'pulsar-off' spectra are then accumulated by finding the pulsar pulse (in time) and extracting spectra during the pulse and between pulses, respectively. The pulsar absorption spectrum is created by generating the 'pulsar-on' – 'pulsar-off' for each observing scan, flattening the baseline by doing frequency switching (or polynomial fitting), and accumulating all such spectra with a weight proportional to $T_{\rm PSR}^2$, where $T_{\rm PSR}$ is the antenna temperature of the pulsar. In the case of multi-epoch observations, the same observing method is repeated several times, with a time interval often ranging from a few days to a few years. Most of the observations presented in this paper were obtained with the Arecibo telescope[1]. Detailed observing and data processing description can be found in Stanimirovic et al. (2003).

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3. ELECTRON DENSITY DISTRIBUTION IN THE GALAXY

The most common method for obtaining pulsar distances is through HI absorption measurements. The basic idea is that the pulsar must be more distant than any HI cloud seen in the absorption spectrum, hence a lower limit can be placed on the pulsar's distance. Under some circumstances the absence of absorption in the presence of HI emission can be used to infer an upper limit on the pulsar's distance (Frail and Weisberg, 1990). The pulsar's distance and dispersion measure can be combined to yield the average free electron density along the line of sight to the pulsar:

$$\langle n(e) \rangle = DM/d. \tag{1}$$

The dispersion measure, DM, is easily obtained from dual frequency arrival time measurements (Weisberg, 1996). With the distance and the average electron density measurement for many pulsars we can build a model of the electron density distribution in the Galaxy. One of the earliest electron density models was put together by Taylor and Manchester (1977) using 149 pulsars. The most recent model by Cordes and Lazio (2003) uses measurements of 1143 pulsars, as well as other galactic and extragalactic sources. Given a Galactic electron density model, equation (1) can be inverted to estimate the distance to any pulsar of known DM.

4. AU-SCALE STRUCTURE IN THE COLD, DIFFUSE ISM

While it has been expected for a long time that structure in the diffuse ISM on scales < 1 pc would not be prominent (Heiles, 2000), surprising, and somewhat controversial detections of cold HI clouds with a typical size of a few tens of AU have been present since 1976 (see Dieter et al., 1976). Frail et al. (1994) suggested that these clouds could be ubiquitous in the ISM, and that 10-20% of the cold neutral medium (CNM) could be in this form. The puzzling thing about these features (often referred to as "TSAS" — tiny-scale atomic structure) is that they are out of local equilibrium and should dissipate on very short time scales. Typical TSAS has a size of ~ 30 AU and an HI column density $\sim 10^{19}$ cm^{-2}. If we assume a simple spherical geometry for these 'clouds', we can estimate their HI volume density, which is typically $\sim 10^4$ cm^{-3}, and the thermal pressure, $\sim 10^6$ cm^{-3} K. These values are at least two orders of magnitude higher from what is expected for traditional CNM clouds, e.g. $n(HI) \sim 42$ cm^{-3} and $P/k = 3000$ cm^{-3} K (McKee and Ostriker, 1977). If TSAS features correspond to descrete HI clouds then their properties are clearly very unusual.

Several different theoretical approaches have been considered in trying to explain TSAS properties and their existence. Stanimirovic et al. (2003) summarizes some of them. We will here just briefly mention the approach by Deshpande (2000) as it offers a simple and direct comparison with observations. Deshpande (2000) suggested that the hierarchy of structures observed on large spatial scales, and represented with a power spectrum, can be extrapolated all the way to the spatial scales of a few AU. Hence, for a given input power spectrum slope, it is possible to predict the level of fluctuations ($\Delta\tau$) that should be measured from observations. While the absolute level of fluctuation may vary spatially, the general trend of $\Delta\tau$ increasing with angular size L should always be present.

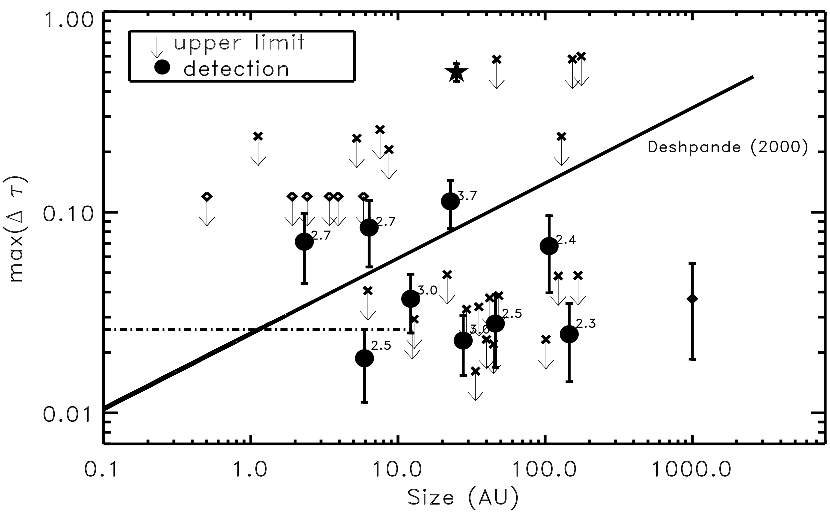

Figure 1: Variations in HI optical depth ($\Delta\tau$), or their upper limits, as a function of spatial scale (in AU) traversed by the pulsars in several recent experiments. The black (filled) circles and crosses represent data from Stanimirovic et al. (2003) and Stanimirovic et al. (2006). The diamonds are from Johnston et al. (2004), and the dot-dashed line is from Minter et al. (2005). The star represents a typical value from Brogan et al. (2005) from VLBA imaging of the continuum source 3C138. The solid line represents the level of variations expected by Deshpande (2000). Upper limits are shown with downward arrows.

In recent years three independent multi-epoch pulsar searches for TSAS were performed using different radio telescopes: Stanimirovic et al. (2003) observed 6 pulsars with the Arecibo telescope with time intervals ranging from about a day to $\sim$ 1.25 years, Johnston et al. (2004) observed 4 pulsars with the Parkes telescope and having time intervals from 6 months to $\sim$ 6 years, and Minter et al. (2005) observed only one pulsar with the Green Bank Telescope but had a large number of observing sessions, with the minimum time interval being 1–2 hours and the maximum time interval being a few weeks.

In the case of the Arecibo experiment only one pulsar, B1929+10, shows significant changes in the HI absorption spectra on several time baselines. Interestingly, B1929+10 has a well established distance of 360 pc and is located close to the boundary of the Local Bubble. Lallement et al. (2003) reported the detection of dense HI clouds inside the Local Bubble relatively close to the direction of B1929+10. Enhanced scattering in the direction of B1929+10 was reported by Bhat et al. (1998), found to be spatially confined and connected to the structure of the Local Bubble. It is possible that the line-of-sight to B1929+10 is sampling the neutral gas at the boundary of the Bubble with the unique origin and properties determined (or at least partially influenced) by the formation mechanism of the Local Bubble.

The more surprising results, however, is the lack of variability of HI absorption spectra found for the majority of pulsars in all three experiments. This large number of non-detections of TSAS suggests that the cold neutral clouds on scales 10^{-2} to 10^{2} AU, traced by pulsar experiments, may not be very common in the ISM. Hence, they may not be a general property of the ISM, but could be related to some local phenomena, like in the case of B1929+10 and its proximity to the Local Bubble. However, pulsar results are very different from those obtained with direct imaging using the VLBA (e.g. Brogan et al., 2005) where significant spatial variations in the HI optical depth are found in the direction of the continuum source 3C138.

We compile here results, both detections and non-detections, from the three pulsar experiments and plot in Fig. 1 variations in HI optical depth ($\Delta\tau$), or their upper limits, as a function of spatial scale traversed by the pulsar. The main idea is to compare the observed level of variations with the predictions of Deshpande (2000). In this figure, crosses and circles show data points from Stanimirovic et al. (2003) and Stanimirovic et al. (2006), diamonds are from Johnston et al. (2004), and the dot-dashed line shows an almost continuous sampling obtained by Minter et al. (2005) on spatial scales < 1 AU. In all cases arrows represent non-detections. We have normalized $\Delta\tau$ values based on the total HI column density seen in emission for particular directions to account for the fact that directions with less HI in general will also show lower $\Delta\tau$. The solid line shows the predicted $\Delta\tau$ vs L line (Deshpande, 2000).

Fig. 1 shows that besides three detections most of detections are at least three times smaller that the predicted value. However, the absolute level of fluctuations is expected to vary across the sky. What should be present though is the general trend, the increase of $\Delta\tau$ with spatial scales L. At this point, observations do not show an obvious increase of $\Delta\tau$ for scales from $< 10^{-1}$ AU to ~ 200 AU. Minter et al. (2005) did not detect $\Delta\tau$ fluctuations consistent with a turbulent spectrum on scales from 2×10^{-3} to 12.5 AU, although the expected level of fluctuations is very small at these scales, often (for scales < 1 AU) smaller than the upper limit provided by Minter at al. Additional data points on scales > 1 AU could be interpreted as the absence of a turbulent spectrum on spatial scales up to ~ 200 AU. This suggests that the cut-off scale for the turbulent spectrum (so called dumping scale) could be $\gtrsim 200$ AU. Yan et al. (2005) discussed different modes of the ISM turbulence and showed that fluctuations driven by the magnetic field are expected to have a cut-off scale of ~ 10 AU, while the incompressible (Alfénic) turbulence has a significantly larger cut-off scale, > 100 AU. Hence, these results may indicate that the incompressible type of turbulence is more important than the compressible type, for the CNM at least.

To add further observational complexity, several observations have recently detected cold HI clouds with extremely low HI column densities (Braun and Kanekar, 2005; Stanimirovic and Heiles, 2005). Observations suggest that these clouds most likely belong to the AU-scale class of objects. Their peak optical depth is 10^{-3} to 10^{-2} and their size is in the range 500–5000 AU. Stanimirovic and Heiles (2005) discussed possible physical mechanisms for the formation of such clouds. It is very difficult for low-$N(HI)$ clouds to survive in the ISM unless they are surrounded by cooler portions of the warm neutral medium (WNM), with $T \sim 10^2 - 10^4$ K. In any case, both TSAS and low-$N(HI)$ clouds must be undergoing evaporation, but this process could take up to 10^6 years, for the coolest WNM case. A slightly different picture of the ISM is provided by simulations of the turbulent ISM (Audit and Hennebelle, 2005; Vazquez-Semadeni et al., 1997) whereby clouds are seen as more transient features undergoing constant transformation. Some transient clouds produced in the simulations have properties similar to those found for the TSAS and low-$N(HI)$ clouds.

5. AU-SCALE STRUCTURE IN THE MOLECULAR GAS

Motivated by the pulsars' unique capabilities for studying the ISM, Stanimirovic et al. (2003) measured the absorption spectra of several pulsars at the wavelength of the hydroxyl radical (OH), $\lambda = 18$ cm, using the Arecibo telescope. OH absorption lines were detected in the case of only one pulsar, B1849+00, and this line-of-sight appears to be particularly interesting. A nearby supernova remnant (SNR) G33.6+0.1 is centered only 8 arcmin south of B1849+00. With its diameter of 10 arcmins, the SNR is even partially covered by the Arecibo beam during these observations. Hence, this experiment allowed a comparison of absorption spectra obtained in the same direction against two types of continuum sources: an almost true point source, B1849+00, and an extended source, G33.6+0.1.

This comparison is shown in Fig. 2. Pulsar OH absorption spectra at 1665 and 1667 MHz are shown in the top two panels representing the pulsar signal *alone* as being absorbed by intervening OH. At a velocity of about 102 km s^{-1} these spectra show deep and narrow absorption lines (labeled as 'A'). However, the same figure shows the pulsar-off spectra in the bottom two panels, which effectively represent OH absorption produced against the continuum emission from G33.6+0.1 *alone*. The absorption features at 102 km s^{-1} look strikingly different. Spectra against B1849+00 have far deeper and narrower absorption lines than the spectra obtained against G33.6+0.1.

One way of explaining this phenomenon is through the clumpiness of molecular gas. If the molecular cloud seen in OH absorption is made up of a lot of small clumps ('cloudlets') then the PSR absorption lines could be produced by a small 'cloudlet', while the shallower, broader absorption features against the SNR could be caused by an ensemble of 'cloudlets' of varying properties. From the comparison of different absorption spectra Stanimirovic et al. (2003) estimated that the 'cloudlet' could have a radius < 1 pc and a hydrogen volume density $n > 10^5$ cm^{-3}.

Recently, Weisberg et al. (2005) observed the same phenomenon in the case of another pulsar, B1641-45. Besides deep absorption lines at 1665 and 1667 MHz, this pulsar also shows an emission line at 1720 MHz. The fascinating thing is that the 1720 MHz emission line cycles up and down with the pulsar's period, on a timescale of a few milliseconds. This demonstrates that pulsar's radiation stimulates production of additional photons at 1720 MHz from the intervening OH cloud. This is a direct evidence for an interstellar amplification of radiation by stimulated emission, or an interstellar maser in action. The duration of amplified emission lasts < 14 milliseconds and switches on and off synchronously with the pulsar pulse. This experiment also shows that maser amplification is possible on extremely short time scales, an effect

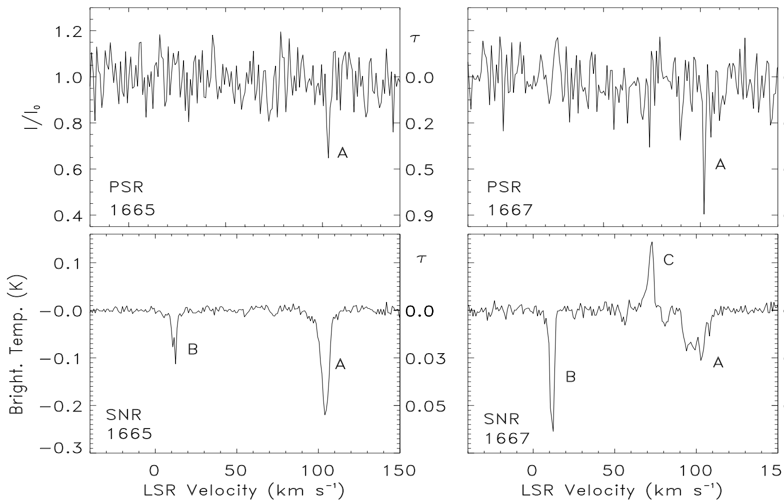

Figure 2: *Top two panels:* Pulsar absorption spectra toward B1849+00 produced against the pulsar continuum emission alone at 1665 and 1667 MHz. *Bottom two panels:* Pulsar-off spectra toward B1849+00 produced against the continuum emission from G33.6+0.1 at 1665 and 1667 MHz. In addition to the absorption system at 102 km s^{-1}, an absorption system at 10 km s^{-1} ('B') and an emission feature at 70 km s^{-1} ('C') are seen.

that may be used in the future to either amplify outgoing signals or to receive amplified signals from extraterrestrial civilizations.

6. CONCLUSIONS

Pulsars have been used as important tools for studying the ISM for several decades. Pulsar radio spectroscopy provides fruitful results, ranging from the measurement of pulsars' kinematic distances and the electron density distribution in the Galaxy, to sampling the ISM properties on AU spatial scales. In addition, recent extensions of this observing technique to the hydroxyl molecule are providing new and exciting insights into the properties of molecular gas and the mechanism of stimulated emission.

Pulsar measurements of the AU-scale structure in the diffuse medium suggest that the cut-off scale for the turbulent spectrum in the CNM may be > 200 AU, emphasizing the importance of the incompressible type of ISM turbulence. The traditional TSAS 'clouds' on AU scales and the low-$N(HI)$ clouds observed on slightly larger spatial scales most likely belong to the same class of objects. These CNM clouds have properties that are challenging classical ISM models. An encouraging similarity was found with the clouds produced in turbulent simulations, suggesting that interstellar 'clouds' may be more transient features than what has been assumed traditionally.

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