The tiny-scale atomic structure: gas cloudlets or scintillation phenomenon?

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Abstract. We present here preliminary results from the recent multi-epoch HI absorption measurements toward several pulsars using the Arecibo telescope. We do not find significant variations in optical depth profiles over periods of 4 months and 9 years. The upper limits on the optical depth variations in directions of B0823+26 and B1133+16 are similar on scales of 10–20, 350 and 500 AU. The large number of non detections of the tiny scale atomic structure suggests that the AU-sized structure is not ubiquitous in the interstellar medium.

Keywords: ISM structure, pulsars

1. Introduction

For many years there have been theoretical and observational support for the existence of structure in the interstellar medium (ISM) on scales from $\sim 1$ pc to 1 kpc (as summarized by Dickey & Lockman 1990), while structure on scales smaller than 1 pc was not believed to have a significant role. As shown in Heiles(2000) it is expected that structure on very small scales ($< 1$ pc) is not prominent in the ISM. Indeed, if we assume the standard thermal pressure for the cold neutral medium (CNM) $P_{th} \sim 2250$ cm$^{-3}$ K (Jenkins & Tripp 2001), and the mean temperature for the CNM of $\sim 70$ K (Heiles & Troland 2003), then the expected volume density for the CNM clouds is about 30 cm$^{-3}$. With the mean measured column density of $1-5 \times 10^{20}$ cm$^{-2}$ (Heiles & Troland 2003), the typical expected scale length for the CNM features is $\sim 1$ pc. It was therefore quite surprising to frequently find structure on AU scales in many different directions in the ISM.

The AU-sized structure is observationally probed using spatial and/or temporal variations in absorption profiles against background sources.
There are several varieties of this observational technique. For the atomic medium, the following three techniques are commonly used. (1) Spatial variation of HI absorption line profiles across the extended background source (Dieter, Welch, & Romney 1976; Diamond et al. 1989; Davis, Diamond, & Goss 1996; Faison & Goss 2001) typically probes scales of a few tens to a few hundreds of AUs. (2) Comparison of optical interstellar absorption lines against binary stars and globular clusters (Meyer & Blades 1996; Lauroesch et al. 1998) probes larger scales of $10^2$–$10^6$ AU. (3) Time variability of HI absorption profiles against pulsars (Deshpande et al. 1992; Frail et al. 1994; Johnston et al. 2003) probes scales of tens to hundreds of AUs. In the case of the molecular medium, the fine-scale structure is usually observed through time and/or spatial variability of molecular line absorption profiles against compact extragalactic sources (Marscher, Moore, & Bania 1993; Moore & Marscher 1995) and typically probes scales of tens of AUs. In this paper we concentrate on the AU-sized structure in the cold atomic medium, often referred to as the tiny-scale atomic structure (TSAS).

The direct quantities provided by observations of the TSAS are optical depth variation ($\Delta \tau$) and a particular time or spatial baseline, which can be translated into transverse size ($L_\perp$). Two additional constraints are the frequency of detection and the variability of the line shape. As the AU-sized structure was very frequently detected it was thought that it is more likely to be a general property of the ISM than the effect of some local phenomena. As noted by Heiles (1997), it is often that the line depth was found to vary rather than the line shape, suggesting that the TSAS is kinematically related to the CNM.

The straightforward and traditional way of interpreting above-mentioned observations is that optical depth variations are due to a blob moving in and out of the line-of-sight, whose transverse dimension is equal to $L_\perp$. Assuming a simple spherical geometry, the HI volume density of these blobs can be estimated and is typically of order of $10^4$ cm$^{-3}$, which is very dense. The inferred thermal pressure is then of the order of $10^6$ cm$^{-3}$ K, much higher than the hydrostatic equilibrium pressure of the ISM or the standard thermal pressure of the CNM. This has been known for a long time and has caused much controversy. It is expected that such over-dense and over-pressured features should dissipate on a time scale of about 100 yrs and therefore not be common in the ISM. A variety of other troubling questions concerning the AU-sized structure includes the following. How are AU-sized features formed and maintained in the ISM? What is the fraction of the ISM occupied by these features? Is this is a new population of interstellar clouds? And is there only one such population or many? How do these
features relate to the continuous hierarchy of structure observed on larger spatial scales?

In order to solve this long-standing puzzle several alternative explanations were proposed. Heiles (1997) suggested that TSAS features are actually curved filaments and/or sheets that happen to be aligned along our line-of-sight. The ratio of the line-of-sight to the plane-of-the-sky length of 4–10 is required to bring the TSAS HI volume density to modest, acceptable, values. Deshpande (2000) suggested that TSAS blobs correspond to the tail of a hierarchical structure organization that exists on larger scales. They pointed out that TSAS observations were misinterpreted by associating measured $L_\perp$ with the longitudinal dimension of TSAS clouds, leading to extraordinary high volume densities. Gwinn (2001) proposed that optical depth fluctuations seen in multi-epoch pulsar observations are actually a scintillation phenomenon combined with the velocity gradient across the absorbing HI of order of 0.05–0.3 km s$^{-1}$ AU$^{-1}$. Different explanations predict a different level of optical depth variations at a particular scale size. For example, Deshpande (2000) expects that optical depth variations would increase with the size of structure, while Gwinn (2001) predicts maximum variations on very small spatial scales probed by the interstellar scintillation. All suggested explanations, however, call for more observational data.

Motivated by the recent theoretical efforts in understanding the nature and origin of the TSAS we have undertaken new multi-epoch observations of HI absorption against a set of bright pulsars. We decided to observe the same sources as Frail et al. (1994) in order to enhance the number of available time baselines for comparison. This paper summarizes preliminary results from this project.

2. Observations and Data Processing

We have used the Arecibo telescope\textsuperscript{1} to obtain new multi-epoch HI absorption measurements against six pulsars previously studied by Frail et. al. (1994). For detail observing and data processing description see Stanimirovic et al. (2003). We had four observing sessions: August 2000, December 2000, September 2001 and November 2001, measuring HI absorption profiles over time intervals from less than a day to 1.25 years. The Caltech Baseband Recorder was used as a fast-sampling backend, with a total bandwidth of 10 MHz, recording the raw voltage data every 100 ns. The first stage of data reduction was performed at the Caltech’s

\textsuperscript{1} The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, operated by Cornell University under a cooperative agreement with the National Science Foundation.
Figure 1. Top: HI absorption spectra against B2016+28 observed in August and December 2000. The HI emission spectrum, obtained in the same direction, has been multiplied by 0.0005. Bottom: Difference between the two absorption spectra. Contours show ±2-σ levels where the HI brightness temperature has been taken into account.

Center for Advance Computation and Research. The ‘pulsar-on’ and ‘pulsar-off’ spectra were accumulated by finding the pulsar pulse 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 scan, doing frequency switching to flat the baseline, and accumulating all such spectra with a weight proportional to $T_{\text{PSR}}$, the brightness temperature of the pulsar. Final absorption and emission spectra have velocity resolution of 0.5 km s$^{-1}$.

3. Results

We present here the results for three pulsars: B0823+26, B1133+16, and B2016+28, from two observing sessions in August 2000 and December 2000. In addition, we have used the third session obtained by Frail et al. (1994) to provide a long term comparison. Fig. 1 shows absorption and emission spectra for PSR B2016+28 from Aug 2000.
Figure 2. Comparison of HI absorption profiles against B2016+28 obtained in December 1991 and December 2000. Details are the same as in Figure 1.

and Dec 2000, while Fig. 2 compares data from Aug 2000 and Dec 1991. The top panel in each figure shows absorption spectra obtained at two different epochs, and a scaled emission spectrum to get a feeling about how noise in the absorption spectra varies with velocity. The bottom panel in each plot shows a difference of absorption profiles at two epochs with overlaid $\pm 2\sigma$ significance envelopes. To estimate the rms noise we have taken into account contribution from the sky background and, very importantly, contribution from the HI brightness temperature which increases the rms noise on line significantly (for example, by a factor of 3 in the case of B2016+28).

For all three pulsars we compared HI absorption spectra over a time span of 4 months (Aug 2000 to Dec 2000) and 9 years (Dec 1991 to Dec 2000). Except for the case of B2016+28 between Aug 2000 and Dec 2000, in all other cases we do not find significant change in the absorption spectra. B2016+28 shows a marginal, 2.5-$\sigma$, change in absorption spectra obtained with a 4 months difference. Transverse velocity of this object is 39 km s$^{-1}$, meaning that during the period of 4 months B2016+28 has traveled over a distance of 3 AU. This marginal detection could be caused by structure on scales of 3 AU.
Other comparisons do not show change in absorption spectra on scales of about 10-20, 70 and 350-500 AU at $\Delta\tau$ level down to about 0.02. Information on individual objects and an upper limit on $\Delta\tau$ are given in Table 1 (note that these are 2-$\sigma$ limits on the HI line). Frail et al. (1994) found variations of 0.07 for B0823+16 and 0.04 for B1133+16 over a period of 13 months. In the case of B2016+28 they noticed even larger optical depth variations of almost 1 over 7 and 20 months periods. Our sensitivity is better than typical variations seen in Frail et al. (1994) and our non detections are therefore a significant result. As already pointed out by Johnston et al. (2003) there is a serious concern that the Frail et al.’s data have been over interpreted. For example, in the case of B2016+28 the noise level on line is at least three times higher than the noise level off line, due to the HI brightness temperature, while Fig. 2 of Frail et al. (1994) claims an increase of no more than 1.5.

The upper limits on optical depth fluctuations set by B0823+26 and B1133+16 at scales of 10–20 and 350–500 AU are strikingly low. $\Delta\tau$ of 0.03 corresponds to $3 \times 10^{18}$ cm$^{-2}$ for the column density fluctuations of the CNM. In addition, these upper limits are almost the same for spatial scales that are more than an order of magnitude different! Deshpande (2000) predicts opacity variations as an extension of HI opacity irregularities observed on larger scales using a single power law spectrum. Using the power spectrum of opacity distribution in the direction of Cas A and extrapolating down to AU scales, they predict $\Delta\tau \sim 0.03$ at scales of about 10 AU, while at 50–100 AU $\Delta\tau \sim 0.2–0.4$ is expected. This model generally expects that $\Delta\tau$ increases with spatial scales. While results for B0823+26 and B1133+16 at scales of 10–20 AU are consistent with this picture, our upper limits for $\Delta\tau$ at scales of 350 and 500 AU for the same pulsars are significantly lower from what is expected. However, this is still a very small number statistics and we will be able to provide stronger constraints on particular theoretical models in the near future. In addition, it is important to mention that the power spectrum slope derived for the direction toward Cas A may not be applicable to directions sampled by pulsars in this study.

This large number of TSAS non detections, together with recent results by Johnston et al. (2003), is disturbing and unexpected! While previous observations were frequently detecting TSAS, in six comparisons presented here, and in many comparisons in Johnston et al. (2003), there is only one marginal detection for the case of B2016+28 and one detection for B1641-45 (Johnston et al. 2003) over a period of almost twenty years. This rises the question of the existence of TSAS as traced at least by multi-epoch pulsars observations. Contrary to the previous belief that the TSAS is ubiquitous in the ISM, our results
Table I. Transverse scales and maximum $\Delta \tau$ probed by the three pulsars. Note that Max. $\Delta \tau$ is a 2-$\sigma$ limit estimated on the HI line.

| PSR       | $L_\perp$ (AU) | Max. $\Delta \tau$ |
|-----------|----------------|---------------------|
| B0823+26  | 10             | < 0.04              |
|           | 350            | < 0.04              |
| B1133+16  | 20             | < 0.03              |
|           | 500            | < 0.02              |
| B2016+28  | 3              | 0.18                |
|           | 70             | < 0.2               |

indicate that TSAS may be more rare and could be related to some kind of a local phenomenon.

4. Conclusions

We have compared multi-epoch HI absorption observations toward B0823+26, B1133+16 and B2016+28 over time periods of 4 months and 9 years. Except for a marginal change in the case of B2016+28 over a 4-month period, we do not find significant changes in absorption spectra. This is very different from previous observations by Frail et al. (1994) who saw significant optical depth variations for the same pulsars over time periods of 7, 13 and 20 months. We have placed upper limits on the optical depth variations of 0.02–0.04 in directions of B0823+26 and B1133+16. In addition, the upper limit on optical depth variations appears the same for spatial scales of 10–20, 350 and 500 AU, traced by these objects. A large number of non detections of the TSAS presented here, together with recent results by Johnston et al. (2003), suggests that the TSAS is not ubiquitous in the ISM.

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