DOES TINY-SCALE ATOMIC STRUCTURE EXIST IN THE INTERSTELLAR MEDIUM?

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ABSTRACT

We report on preliminary results from the recent multiepoch neutral hydrogen absorption measurements toward three pulsars, B0823+26, B1133+16, and B2016+28, using the Arecibo telescope. We do not find significant variations in optical depth profiles over periods of 0.3 and 9–10 yr or on spatial scales of 10–20 and 70–85 AU. The large number of nondetections of the tiny-scale atomic structure suggests that the AU-sized structure is not ubiquitous in the interstellar medium and could be quite a rare phenomenon.

Subject headings: ISM: clouds — ISM: structure — line: profiles

1. INTRODUCTION

For many years, both observations and theory have provided extensive support for the existence of structure in the interstellar medium (ISM) on scales from ~1 kpc down to ~1 pc (e.g., Dickey & Lockman 1990). However, it has long been expected that structure on smaller scales (<1 pc) would not be prominent in the ISM (Heiles 2000). Indeed, using median values for thermal pressure and temperature of the cold neutral medium (CNM) of $P_{\text{th}} \sim 2250 \text{ cm}^{-3} \text{ K}$ (Jenkins & Tripp 2001) and $T \sim 70 \text{ K}$ (Heiles & Troland 2003), the expected volume density of the CNM clouds is about $30 \text{ cm}^{-3}$. The median measured column density of $5 \times 10^{19} \text{ cm}^{-2}$ (Heiles & Troland 2003) would then indicate that the typical expected scale length for the CNM features is ~1 pc, in conformance with the standard theory and observations.

Consequently, it was quite surprising when observers began to find structure on $10^3$–$10^2$ AU scales in many different directions in the ISM. The apparent detections of the AU-sized structure in the cold neutral atomic medium, called tiny-scale atomic structure (TSAS; Heiles 1997), were obtained with the following techniques: (1) spatial mapping of neutral hydrogen (H i) absorption-line profiles across extended background sources (Dieter, Welch, & Romney 1976; Diamond et al. 1989; Davis, Diamond, & Goss 1996; Faison & Goss 2001), (2) temporal and spatial variations of optical interstellar absorption lines for comparison. This Letter summarizes our first results (1994) in order to enhance the number of available time base-lines for three pulsars, B0823+26, B1133+16, and B2016+28. In § 2 we summarize our observing and data processing strategies. Results on individual objects are presented in § 3 and discussed in § 4.

2. OBSERVATIONS AND DATA PROCESSING

We have used the Arecibo telescope\textsuperscript{1} to obtain new multiepoch H i absorption measurements against six pulsars pre-

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3. Results on Individual Sources

For each pulsar, we display a single absorption spectrum on top and then one or more absorption spectrum differences between two epochs. Overlaid atop each difference spectrum is a ±2σ significance envelope. To calculate this expected noise level, we have taken into account the following contributions. (1) The sky background contribution was estimated from the all-sky survey at 408 MHz by Haslam et al. (1982) and scaled to 1.4 GHz using a spectral index of −2.6. (2) The contribution from H1 emission was estimated from the pulsar-off spectra and scaled appropriately to match previously published observations. The effect of this contribution can be very significant. For example, the rms noise on-line is 3 times higher than the rms noise off-line for the case of B2016+28. (3) The pulsar continuum emission itself is also sufficiently strong to contribute an additional ~10%–30% to the noise temperature. Information on individual objects and an upper limit on Δτ are given in Table 1 (note that these are 2σ limits at the H1 line). Our measurements and the Frail et al. (1994) results are discussed for each source below.

**PSR B0823+26.**—Figure 1 (left) compares H1 absorption profiles obtained toward B0823+26 in 2000.6 and 2000.9. We find no significant change in absorption over this time span down to a Δτ level of about 0.04. The time interval of 0.3 yr translates to a transverse distance of about 10 AU. Frail et al. (1994) also found almost no variations over a period of 0.6 yr but did report variations of about 0.07 over a period of 1.1 yr. See §4 for an examination of the discrepancies between the two groups’ results.

**PSR B1133+16.**—Figure 1 (right) displays H1 absorption profiles obtained toward B1133+16 in 2000.6 and 2000.9. We detect no variations down to a Δτ level of about 0.02. During this period, the pulsar traveled 20 AU. Frail et al. (1994) also detected no significant variations on their 0.6 yr baseline on this pulsar but did see variations in τ of about 0.04 over a period of 1.1 yr. We investigate the discrepancy below.

**PSR B2016+28.**—For this pulsar, we have compared H1 absorption profiles on our usual short (~0.3 yr) timescale but also on decade-long scales. On the left side of Figure 2 (middle)

| PSR    | Lτ (AU) | Maximum Δτ |
|--------|---------|------------|
| B0823+26 | 10      | <0.04      |
| B1133+16 | 20      | <0.03      |
| B2016+28 | 3       | 0.18       |
|        | 70      | <0.20      |
|        | 80      | 0.15       |
|        | 85      | <0.20      |

**Notes.**—Note that upper limits on Δτ correspond to 2σ noise on the H1 line while the two values of Δτ that are not upper limits lie beyond the 2σ noise. The longest spatial baseline for B2016+28 corresponds to the difference between the 2000.6 spectrum and the 1990.3 spectrum from Frail et al. 1994 and is not shown in the Letter. Transverse velocities used to calculate Lτ are given in Frail et al. 1994.
we show the usual difference of absorption spectra from 2000.6 and 2000.9, while the bottom left panel investigates an 8.7 yr interval by differencing our 2000.6 spectrum and the Frail et al. (1994) 1991.9 data. The 0.3 yr baseline, corresponding to a ∼3 AU scale, shows only a marginal 2.6 σ change in absorption, while the 8.7 yr ∼70 AU baseline does not exhibit any significant variations at all. This result is very different from Frail et al. (1994), who found very large optical depth variations of Δτ ∼ 1 over periods of 0.6 and 1.7 yr.

The Frail et al. (1994) epoch 1991.9 absorption spectrum that we use for the above comparison is particularly different from the previous three Frail et al. epochs (their first one actually being from Clifton et al. 1988). While it agrees well with our epoch ∼2000 results, their 1991.9 profile exhibits significantly shallower absorption in all four principal absorption features than do their earlier epoch results. Frail et al. (1994) remarked that the apparent change could be caused by an incorrect normalization but were confident that was not the case.

We further investigate the apparent Frail et al. variations by comparing our 2000.6 spectrum with the pre-1991.9 Frail et al. profiles. As expected, there is a large difference in the depth of all four absorption features, as shown in the top plot on the right side of Figure 2, where the 1990.9 Frail et al. spectrum is plotted with a dot-dashed line and our 2000.6 result is plotted as a thin solid line. Since all four lines exhibit the same trend, it seems reasonable that the differences may result from a slight calibration problem in the Frail et al. data. To test this hypothesis, we performed a least-squares fit for a single scale factor (plus an offset) that would minimize the difference between our 2000.6 and scaled 1990.9 spectra. A single 3 σ deviation is all that remains. Note that without scaling, this change would be much larger. We conclude that most of the apparent variations among the Frail et al. B2016+28 spectra, and hence between our epoch 2000.6 data and the early Frail et al. epochs, could result from a systematic calibration issue in the Frail et al. data. The measurement of pulsar absorption spectra is a very delicate process fraught with subtle issues related to the strongly varying pulsar signal. We speculate that the three-level correlation spectrometer used by Frail et al. was more prone to calibration problems than our current four-level spectrometer.

4. DISCUSSION

Our observations probe the existence of temporal variations in H I absorption profiles that would be indicative of the existence of the TSAS on spatial scales of several tens of AU in several different directions. The canonical TSAS has L⊥ ∼ 30 AU, extracted by Heiles (1997) from previous observations, meaning that TSAS should be common at the scales that we have studied. Yet in all of the short and long baselines that we have investigated, we find only two marginal detections of changing absorption.

Our sensitivity is better than any level of variations reported previously (Frail et al. 1994; Johnston et al. 2003), at velocity resolution of 0.5 km s⁻¹, meaning that our nondetections are a significant result. In addition, the upper limits on optical depth fluctuations, set by B0823+26 and B1133+16 at scales of 10–20 AU, Δτ = 0.03–0.04, are strikingly low. A Δτ of 0.03 corresponds to 5 × 10¹⁸ cm⁻² for the column density fluctuations of the CNM, for assumed spin temperature of 50 K, and the FWHM of absorption features of 2 km s⁻¹. On slightly larger scales of 70–80 AU probed by B2016+28 over periods of almost a decade, we find a single 3 σ spike of Δτ = 0.15, a ~2.5 σ feature of Δτ ~ 0.18, and nondetections in all other cases.

Deshpande (2000) predicts opacity variations as an extension
of H I 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 with the power-law index of 2.75 and extrapolating down to AU scales, they predict $\Delta \tau < 0.1$ at scales $\sim 20$ AU (from their Fig. 2), 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. Our results for all three pulsars seem consistent with this picture so far.

Why are the (primarily) nondetections presented here and by Johnston et al. (2003) so different from the results of Frail et al. (1994)? We showed above that in the case of B2016+28 in which multiple absorption features are visible, it is possible to simply scale absorption spectra from different epochs and get rid of most of the variations, indicating that slight calibration problems may be responsible. A similar scaling technique could significantly reduce variations seen in some of the other Frail et al. pulsars (e.g., B0823+16, B1133+6, and B1737+13). However, it is not obvious that this scaling could be justified, since only single principal absorption features are visible in the spectra. In addition, Johnston et al. (2003) have already noted that many of the differences noted by Frail et al. may not be as significant as they stated.

This large number of TSAS nondetections, 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 are only two marginal detections for B1641–45 (Johnston et al. 2003) over a period of almost 20 yr. This raises the question of the existence of TSAS as traced at least by multiepoch pulsars’ observations. Contrary to the previous belief that the TSAS is ubiquitous in the ISM, our results indicate that TSAS is rather rare and could be related to some kind of isolated sporadic events such as superbubble or supernova expansion, stellar mass ejecta, or a bow shock propagation.

5. CONCLUSIONS

We have compared multiepoch H I absorption observations toward B0823+26, B1133+16, and B2016+28 over short and long periods. Except for two marginal changes in the case of B2016+28, 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 1.1 and 1.7 yr. We have shown that in the case of B2016+28, most of the variations in absorption profiles of Frail et al. (1994) could be due to a systematic calibration problem. A large number of nondetections of the TSAS presented here, together with recent results by Johnston et al. (2003), suggests that the TSAS is not ubiquitous in the ISM and could be a rare phenomenon.

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