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Pulsar Studies of Tiny-Scale Structure in the Neutral ISM

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Abstract.
   We describe the use of pulsars to study small-scale neutral structure in the interstellar medium (ISM). Because pulsars are high velocity objects, the pulsar-Earth line of sight sweeps rapidly across the ISM. Multiepoch measurements of pulsar interstellar spectral line spectra therefore probe ISM structures on AU scales. We review pulsar measurements of small scale structure in HI and OH and compare these results with those obtained through other techniques.

1.   Introduction

The discovery of tiny-scale atomic structure (TSAS; Heiles (1997)) in the neutral interstellar medium (ISM) was made in the VLBI neutral hydrogen (HI) absorption experiment of Dieter et al. (1976).[1] Meanwhile, a complementary technique for probing tiny-scale structure, using multiepoch pulsar observations, began in the mid-1980s. This technique takes advantage of pulsars' compact nature and their high velocities to probe the ISM on tiny scales by searching for temporal variations in spectral lines produced by the intervening medium. Until recently, these studies were confined to neutral hydrogen 21 cm absorption lines, but in the last few years the technique has been extended to investigations of OH in both absorption and stimulated emission.

2.   The Technique

Pulsars subtend very small angles on the sky, even after their intrinsic size is broadened by interstellar scattering. They tend to be high-velocity objects, with transverse speeds of hundreds of km s^{-1}. Consequently the pulsar-Earth column probed by a pulsar signal is both needle thin and is dragged in short order across solar system size scales in the ISM. For example, a 100 km s^{-1} transverse pulsar velocity sweeps the line of sight across 20 AU in one year. Multiepoch pulsar

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[1]See Brogan et al, this volume, for a review of interferometric studies of tiny-scale structure.

ISM measurements at reasonable intervals then probe ISM structure on these scales.

In order to study the medium along the line of sight, one must measure the *pulsar ISM spectrum*[2] at and near the frequency of a spectral line such as $\lambda \sim 21$ cm HI or $\lambda \sim 18$ cm OH. The pulsar ISM spectrum, which is the spectrum of the pulsar *alone* (as modified by the intervening ISM) is not a direct observable since the telescope samples a complicated combination of signals throughout its beam. Some form of beam switching or spatial filtering is employed to separate the ISM spectrum of conventional steady sources. However, because of the pulsed nature of pulsar emission, it is straightforward in principle to derive the pulsar ISM spectrum via *temporal* switching; i.e., by differencing measurements of the spectrum when the pulsar is *on*, $I_{PSR-On}(\nu)$; and when it is *off*; $I_{PSR-Off}(\nu)$:

$$I_{PSR-ISM}(\nu) = I_{PSR-On}(\nu) - I_{PSR-Off}(\nu). \tag{1}$$

Ultimately we desire the fractional absorption or fractional stimulated emission, $I_{PSR-ISM}(\nu)/I_{PSR,o}$ where $I_{PSR,o}$ is the unabsorbed pulsar intensity determined from off-line spectral channels, or equivalently the (positive or negative) optical depth $\tau(\nu)$ of the gas along the pulsar-Earth line of sight, defined by

$$\tau(\nu) = -\ln(I_{PSR-ISM}(\nu)/I_{PSR,o}). \tag{2}$$

Early efforts utilized one-bit spectrometers whose output was gated synchronously with the pulsar period into one of two buffers (pulsar-*on* or pulsar-*off*). Calibration of the spectra was difficult because of limitations inherent in one-bit sampling of the wildly varying pulsar signal (Weisberg et al. 1980). Some of these limitations have been lessened through the years with the introduction of multibit spectrometers whose output can be directed into multiple pulsar phase bins rather than only two. The resulting multibit cube of data (intensity as a function of frequency and pulsar phase) can then be optimally processed to yield the pulsar-*on*, pulsar-*off*, and pulsar ISM spectra. Nevertheless, careful calibration remains crucial since the desired pulsar ISM spectrum represents the (usually small) difference between two very similar spectra.

3.   Neutral Hydrogen Measurements and Analyses

As hydrogen is the most pervasive constituent of the ISM, it is natural to study fluctuations in HI. This section examines the pulsar and interferometric HI experiments and analyses.

3.1.   History of Pulsar Tiny-Scale HI Structure Experiments

Early efforts with the pulsar HI ISM technique focused on measuring pulsar distances kinematically. This procedure continues to have great success, and provides primary calibration (e.g., Frail & Weisberg (1990); Weisberg (1996)) for

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[2]Historically the relevant spectrum was called the "pulsar *absorption*" spectrum, but recent observations of pulsar-stimulated OH *emission* require that the term "absorption" be replaced when describing this technique generically.

models of the galactic density distribution (Taylor & Cordes 1993; Cordes & Lazio 2002). By the late 1980s, sufficiently accurate repeated measurements began to be made, and it was noticed that the pulsar ISM spectra changed over time in some cases, suggesting changes in the tiny-scale structure of intevening gas. For example, Clifton et al. (1988) found that the HI absorption spectrum of PSR B1821+05 changed significantly between 1981 and 1988, with the appearance at the latter epoch of a previously unobserved feature with $\tau \sim 2$ and $\Delta v \sim 1$ km s^{-1}. Deshpande et al. (1992) showed that between ~ 1976 and 1981, HI absorption toward B1154-52 did *not* change significantly; while toward B1557-50, a variation with $\Delta\tau \sim 1$ was interpreted as a cloud of size in the 1000 AU range.

These early pulsar HI results inspired Frail, Weisberg, Cordes, & Mathers (1994) to mount a dedicated multiepoch pulsar HI absorption experiment at Arecibo. Six pulsars were observed at three epochs, with time baselines ranging from 0.7 - 1.7 yr. These authors reported the presence of *pervasive* variations with $\Delta\tau \sim 0.03 - 0.7$, and associated HI column densities of $10^{19} - 5 \times 10^{20}$ cm^{-2}; on scales of 5-100 AU. They indicated that 10-15% of cold HI is in the tiny structures, and additionally detected a correlation between absorption equivalent width variations and equivalent width itself. These results appeared to buttress the earlier VLBI findings of small scale structure, and they provided a strong impetus for further experimental and theoretical work.

The theoretical work focused on explaining the very existence of TSAS. The presence of such structures is enigmatic, especially because they appear to be significantly overpressured with respect to the ambient ISM. Heiles (1997) emphasized the seriousness of the overpressure problem, and suggested that nonspherical cloud geometries such as filaments and sheets oriented with their long axes along the line of sight could ameliorate it. Deshpande (2000) argued that the observed changes do not result from discrete structures, but rather are merely the variations expected from a reasonable power-law spectrum of opacity fluctuations. Gwinn (2001) showed that velocity gradients in the HI, combined with interstellar scattering of the pulsar signals, could explain the variations.

3.2. Recent Pulsar HI TSAS Measurements

The recent era of pulsar TSAS experiments began with the Parkes observations of Johnston et al. (2003). Surprisingly, these investigators found no significant optical depth variations in their three-epoch, 2.5-yr observations of three pulsars, and were able to place an upper limit on column density variations toward PSR B1641-45 of 10^{19} cm^{-2}, significantly below the Frail, Weisberg, Cordes, & Mathers (1994) detections. They showed that the earlier experiment did not fully account for the large increases in noise in absorption spectra at the line frequency, so that some of the apparently significant variations actually were not. While no significant variations were seen by Johnston et al. (2003) during the 2.5 years of their TSAS experiment, they detected variations in the spectrum of PSR B1557-50 when compared with measurements made five years earlier. This is the same pulsar whose spectrum was noted earlier by Deshpande et al. (1992) to vary on similar timescales in the late 1970s. In combining the results from four measurements over twenty-five years, Johnston et al. (2003) concluded that the cloud causing the variations is ~ 1000 AU in size, with a density of $\sim 10^{4}$ cm^{-3}.

Minter et al. (2005) performed a particularly exhaustive TSAS study on PSR B0329+54, which is very bright and almost circumpolar at the Green Bank Telescope. The investigators observed the pulsar continuously for up to 20 h in eighteen observing sessions over a period of 1.3 yr. They detected no HI opacity variations ($\Delta\tau < 0.026$ in most cases) for pulsar transverse offsets ranging from 0.005 - 25 AU.

The New Arecibo Pulsar HI TSAS Experiment   Recently, we and our colleagues instigated a new set of Arecibo multiepoch pulsar HI TSAS studies. Advances in digital technology since the earlier observations of Frail et al. (1994) allowed the use of a multibit spectrometer (Jenet et al. 2001) whose calibration should minimize systematic errors; and receiver improvements decreased the noise. Preliminary results were published by Stanimirović et al. (2003a) and a final report is nearing completion (Stanimirović et al. 2007). We observed the same six pulsars as Frail et al. (1994) at four epochs, yielding time baselines between 0.2 and 1.3 yr, with pulsars moving between 1 and 200 AU between sessions. The line of sight parameters for the six pulsars are given in Table 1.
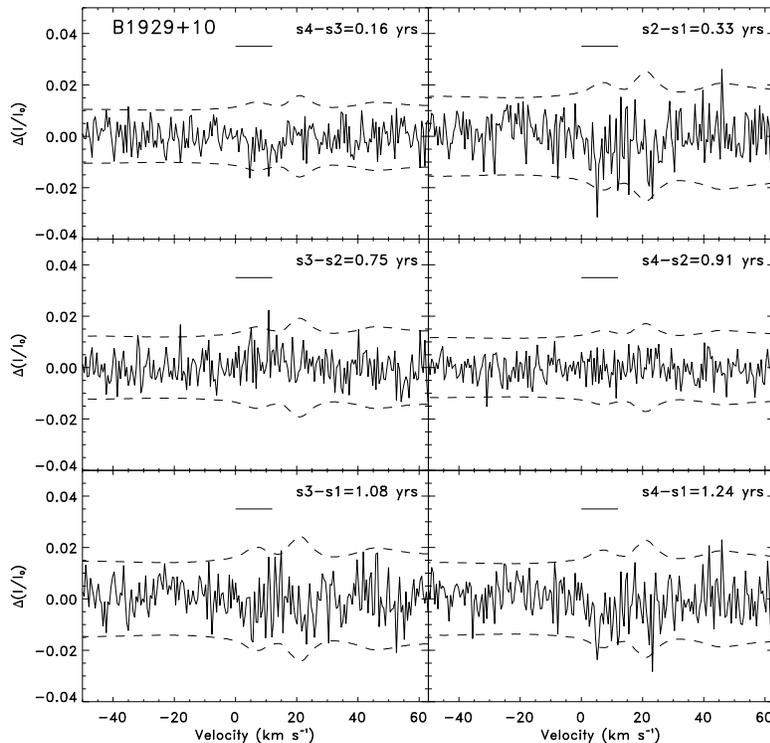

Figure 1.   Differences between pairs of HI absorption spectra for B1929+10. Data were gathered at Arecibo by Stanimirović et al. (2007). The horizontal bar delineates the velocity range where significant absorption is present in single-epoch spectra. Dashed lines show $\pm 2\sigma$ error envelopes. Note that only a few features extend outside the envelopes.

Table 1.   Line of sight parameters in the Arecibo pulsar HI TSAS study

PSR J	PSR B	l (deg)	b (deg)	d (kpc)	$v_{transverse}$ (AU / yr)
J0543+2329	B0540+23	184	-3.3	3.5	80
J0826+2637	B0823+26	197	32	0.4	40
J1136+1551	B1133+16	242	69	0.4	130
J1740+1311	B1737+13	37	22	4.7	140
J1932+1059	B1929+10	47	-3.9	0.3	40
J2018+2839	B2016+28	68	-4.0	1.0	7

For each pulsar, we differenced the six pairs of absorption spectra corresponding to the four observing sessions. We found few statistically significant optical depth variations. The rare cases of significant changes were mostly seen toward PSR B1929+10 and PSR B2016+28 (see Figs. 1 and 2). The detections result from variations having column densities of $\sim 10^{18-19}$ cm^{-2}, with implied volume densities (for spherical clouds) of $\sim 10^{4-5}$ cm^{-3}. It is worth noting that the PSR B1929+10 fluctuations have a factor of 3-4 lower column densities than the "canonical" HI TSAS discussed by Heiles (1997).

We have also studied the *integrated* properties of the variations using equivalent width EW, where EW=$\int \tau dv$. Fig. 3 shows $|\Delta \text{EW}|$ versus EW for all our pulsars except B0540+23, whose optical depth integrals become very uncertain near $\tau \sim \infty$ features. PSR 1929+10 exhibits the only significant ($> 3\sigma$) nonzero values of $|\Delta \text{EW}|$. Our results on PSRs B1737+13 and particularly B2016+28 [primarily upper limits with an occasional marginal ($< 2\sigma$) detection] are far lower than the detections of Frail, Weisberg, Cordes, & Mathers (1994) [$|\Delta \text{EW}| \leq 0.2$ *vs.* $|\Delta \text{EW}| \sim 0.5$ for B1737+13 and $|\Delta \text{EW}| \leq 0.3$ *vs.* $|\Delta \text{EW}| \sim (1-5)$ for B2016+28]. We believe that at least some of the variations they saw were due to small calibration errors. Our results do not rule out their finding of a correlation between $|\Delta \text{EW}|$ and EW, but the evidence for such a trend appears marginal in our data.

3.3.   A Sketch of Recent Interferometric HI TSAS Experiments

The state of the art of interferometric measurements of HI TSAS has also advanced significantly since the first detection of Dieter et al. (1976), especially with the advent of the VLBA. The sources 3C 147 and 3C 138 show the most prominent fluctuations. Faison & Goss (2001), who have done the most recent observations and analyses of 3C 147, find $\Delta \tau \sim 0.3$ over ~ 25 AU scales. The newest results on 3C 138 by Brogan et al. (2005) indicate variations of $\Delta \tau \sim 0.5$ on 25 AU scales. The fluctuations appear in approximately 10% of their pixels on the source. Most modern interferometer results on other sources yield smaller and less frequent optical depth variations (Faison et al. 1998). See the contribution by Brogan et al in this volume for a thorough review of these measurements.
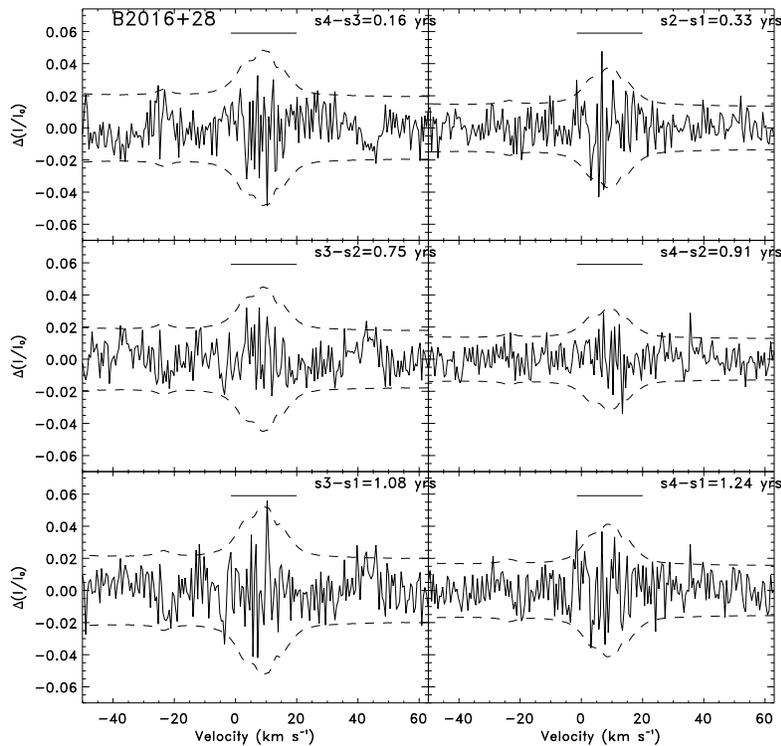
Figure 2.   Differences between pairs of absorption spectra for B2016+28.
See Fig. 1 for details.

3.4.   Discussion of HI TSAS Results

The various pulsar and interferometric measurements reviewed above appear
to lead to divergent conclusions about the properties and pervasiveness of HI
TSAS. Yet Occam's Razor suggests that we search for the simplest explanation
that can explain them all.

Among the pulsar measurements, it appears that Frail et al. (1994), who
found that TSAS is rather pervasive, provide the principal outliers. We have
noted above that there appear to be calibration issues in these measurements
which may have led to overestimates of the prevalence of optical depth varia-
tions. In our subsequent analyses, we have replaced their results with our newer
measurements of the same pulsars (Stanimirović et al. 2007).

Brogan et al. (2005) note that the two sources exhibiting the most signif-
icant evidence for TSAS among HI interferometer results, 3C 138 and 3C 147,
are also the only two with angular sizes significantly larger than the detected
gas fluctuations. They propose that the lower measured levels of variations in
the other cases results from a selection effect due to incomplete sampling of the
relevant angular and spatial scales. They also attempt to model pulsar results by
studying the statistics of one-dimensional spatial cuts across the face of 3C138.
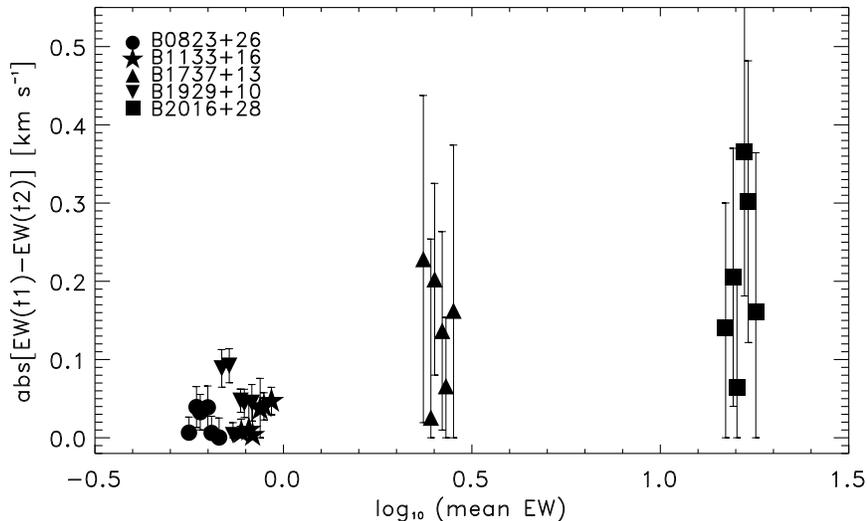They conclude that the relatively low level of recent pulsar TSAS detections

Figure 3.   Equivalent width changes $|\Delta$EW$|$ versus EW in the pulsar HI experiment of Stanimirović et al. (2007), where equivalent width EW$=\int \tau dv$.

can also be explained by an incomplete sampling of angular scales due to the episodic nature of the observations. However, their model pulsar observations are all separated by the same angular scale, namely the characteristic scale of the HI fluctuations; whereas multiepoch observations of a given pulsar actually sample a variety of scales. The recent observations of Minter et al. (2005), published after the Brogan et al. (2005) analysis was complete, are particularly notable in finding no fluctuations over a very wide and almost continuous range of scales.

In an attempt to make progress toward a comprehensive explanation of the various observations, we have plotted HI TSAS detections and upper limits as a function of their spatial scale in Fig. 4. The expected level of optical depth variations as a function of scale calculated from the Deshpande (2000) power law fluctuation model is also shown as a sloping line. As these values are extrapolated from much larger observed scales, they could be significantly in error but the slope is more secure.

We note that the Brogan et al. (2005) interferometric detection is at a higher level than any other, which suggests that the line of sight may indeed have a higher level of fluctuations than is typical. Note however that several of our pulsar detections at slightly smaller scales (mostly PSR 2016+28), though exhibiting somewhat lower optical depths, are consistent with the Brogan et al. (2005) detection if the Deshpande (2000) power law slope is correct. Meanwhile numerous other pulsar detections and upper limits lie well below the above mentioned ones; most especially our PSR B1929+10 results and the Minter et al. (2005) upper limits over a wide range of scales. The figure also emphasizes that pulsar TSAS experiments have made detections on many spatial scales, whereas the two most secure interferometric results both yield a single scale of ~ 25 AU
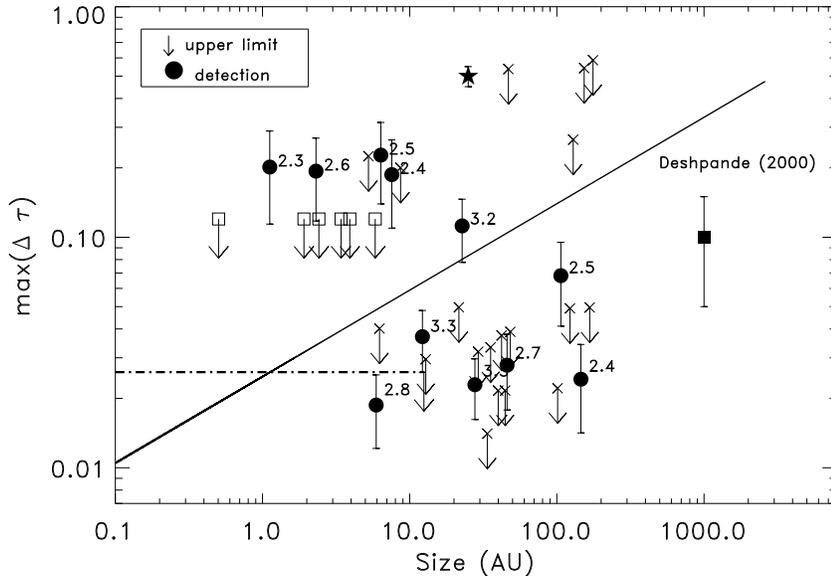
Figure 4.   HI optical depth fluctuations as a function of spatial scale.
The Brogan et al. (2005) interferometric 3C 138 fluctuations (star), the
Johnston et al. (2003) pulsar detection (filled square) and upper limits (open
squares), the Minter et al. (2005) pulsar upper limits (dot-dashed horizontal
line), and Stanimirović et al. (2007) pulsar detections (filled circles) and up-
per limits (crosses) are shown, along with the Deshpande (2000) theoretical
expectation (sloping line). The depth of the fluctuation in units of σ is placed
next to each detection.

(Brogan et al. 2005). Hence we conclude that the observed variations in level
and scale of HI TSAS are more than a selection effect, and that they are strongly
dependent upon local conditions along a particular line of sight.

Recently Braun & Kanekar (2005) and Stanimirović & Heiles (2005) have
detected a population of small (10^{3-4} AU) HI clouds via very sensitive absorp-
tion measurements of extragalactic background sources. The optical depths and
column densities range below 1 % and 10^{18} cm^{-2}, respectively. It is not yet clear
whether these features represent a distinct population or merely an extension of
the pulsar-detected TSAS toward larger spatial size and smaller optical depth.

We have examined the lines of sight toward our two pulsars with the most
significant fluctuations. Nothing particular was found in the direction of PSR
B2016+28. However, the line of sight toward PSR B1929+10 appears to run
along the wall of the Local Bubble for a significant stretch, according to the map
of Lallement et al. (2003). While the Local Bubble itself is probably a relatively
quiescent region, its boundary is thought to be marked by enhanced turbulence
(Phillips & Clegg 1992). We currently regard this finding as potentially impor-
tant but tentative, and we await further refinements in knowledge of the location
of the Local Bubble boundary.

4. Studies of Molecular Tiny-Scale Structure

The tiny-scale structure of molecular gas in the ISM is an interesting area for investigation, both in its own right and in comparison with neutral atomic hydrogen (§3). Interstellar molecular spectral lines usually have much smaller optical depths than HI, making them harder to detect. Therefore most successful radio observations of small scale structure in molecular gas awaited relatively recent advances in sensitivity and angular resolution.

Marscher et al. (1993) and Moore & Marscher (1995) did a series of molecular absorption line experiments using extragalactic background sources. They detected significant time-variable 4.8 GHz H_2CO absorption with $\Delta\tau = 0.02 - 0.03$ in front of two compact sources, which they interpret as resulting from the superposition of several clumps along the line of sight whose size is ~ 10 AU or less, having HI column densities of $\sim 10^{20}$ cm^{-2} and volume densities of $\sim 10^6$ cm^{-3}.

Pulsars can be excellent probes of molecular gas for all the reasons given in §2, providing only that the pulsar signal is sufficiently strong at the line frequency. However, pulsars have rather steep spectra, so the only lines matching this criterion are the four 18 cm lines of OH.

The first published pulsar OH ISM experiments were done by Slysh (1972) and Galt (1974). Both of these investigators detected no absorption in the spectrum of PSR B0329+54; while Slysh detected no absorption in several others. His detection of OH absorption at 1667 MHz in PSR B1749-28 was not confirmed by later observations.

Taking advantage of the high sensitivity of Arecibo, we and our colleagues did the first modern pulsar studies of interstellar OH (Stanimirović et al. 2003b). Among the seven pulsars studied, only PSR B1849+00 clearly exhibits OH absorption. This line of sight is remarkable in that it passes near the edge of the SNR Kes 79 (G33.6+0.1). Fig. 5 displays our OH spectra gathered in this direction. The absorption lines in the pulsar-off spectra (bottom row) result from SNR continuum radiation being absorbed by foreground gas. Note that these pulsar-off absorption lines exhibit much smaller optical depths than do the pulsar OH spectra (top row) at $v \sim 100$ km s^{-1} ($\tau \sim 0.05$ *vs*. 0.4 at 1665 MHz and $\tau \sim 0.02$ *vs*. 0.9 at 1667 MHz). These smaller pulsar-off optical depths are much more representative of typical OH absorption optical depths in the plane (e.g., Dickey et al 1981), so that our measured pulsar OH optical depths are anomalously high. Stanimirović et al. (2003b) discuss several possible explanations for the high optical depths in the pulsar OH interstellar spectra. The most likely is that the tiny column through the ISM sampled by the pulsar signal has encountered a small ($< 15''$), high density ($> 10^5$ cm^{-3}) molecular cloudlet. Meanwhile, the pulsar-off spectrum, in sampling absorption across the full telescope beam, represents a solid-angle average across a clumpy medium consisting of relatively high optical depth, small molecular cloudlets, embedded in a lower density medium.

Weisberg et al. (2005) continued the search for additional pulsar OH interstellar lines with the Parkes telescope. Of eighteen pulsars searched, only B1641-45 exhibited detectable pulsar ISM spectra (see Fig. 6). Note that the pulsar ISM spectra (right column) exhibit significantly larger optical depths than do the corresponding pulsar-off spectra (left column), continuing the trend
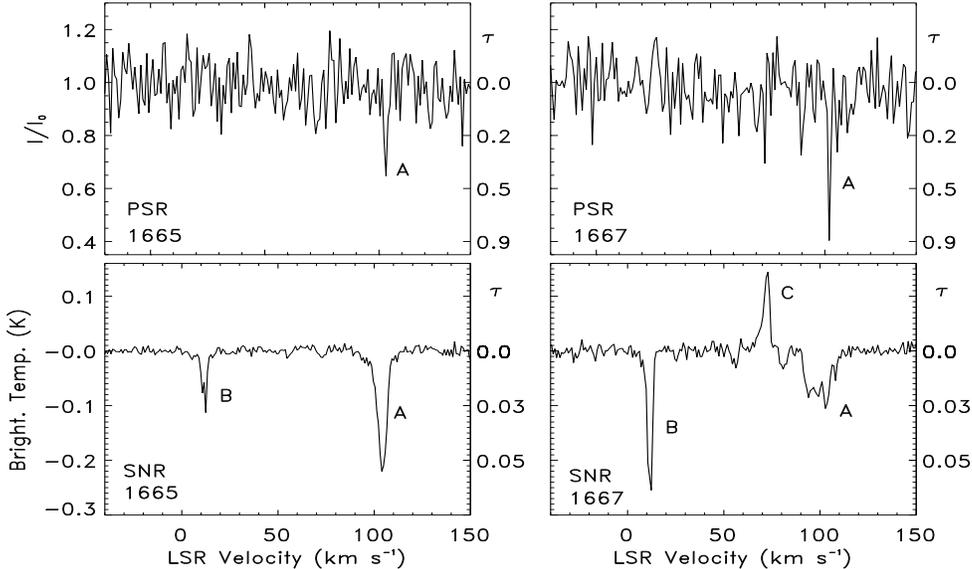
Figure 5. Arecibo OH spectra toward PSR B1849+00, after Stanimirović et al. (2003b). The top row shows the pulsar ISM spectra at 1665 and 1667 MHz. The bottom row, taken when the pulsar is off, shows emission and absorption throughout the telescope beam, which is filled by the SNR Kes 79 (G33.6+0.1). Compare pulsar ISM optical depths (top) with pulsar-off, SNR optical depths (bottom).

discussed above in PSR B1849+00. So it again appears that the pulsar-Earth pencil beam has intercepted dense cloudlets in the pulsar ISM spectra, whose properties suffer angular dilution in the pulsar-off spectra. Note also that stimulated emission is present in the 1720 MHz pulsar ISM spectrum. This is the first detection of a pulsed interstellar maser. Since the stimulated emission appears in the spectrum of the pulsar alone, it represents a direct demonstration that the emission is stimulated by pulsar photons.

Minter (2005) has also recently searched for OH lines in the spectra of five pulsars with the GBT. He detected absorption toward PSR B1718-35.

4.1.   Discussion of Molecular Results

Theory suggests that molecular clouds are a dynamic, turbulent environment (Mac Low & Klessen 2004; Bonnell et al. 2006). Brunt & Heyer (2002) performed a principal component analysis of CO maps, finding a slope of 2.17 for the energy spectrum, which they interpreted as evidence for continuous energy injection at small scales. Thus it is not surprising that both the formaldehyde results and our groups' pulsar OH work indicate the presence of tiny-scale structure in molecular gas. Our conclusions result from our detection of larger optical depths in the pulsar ISM spectra than in the pulsar-off spectra. Multiepoch experiments are now in progress to search for time variability in the these lines, much like the pulsar HI experiments of §3.1 and 3.2. Detection of time variability will provide powerful additional support for the existence of TSAS in OH.
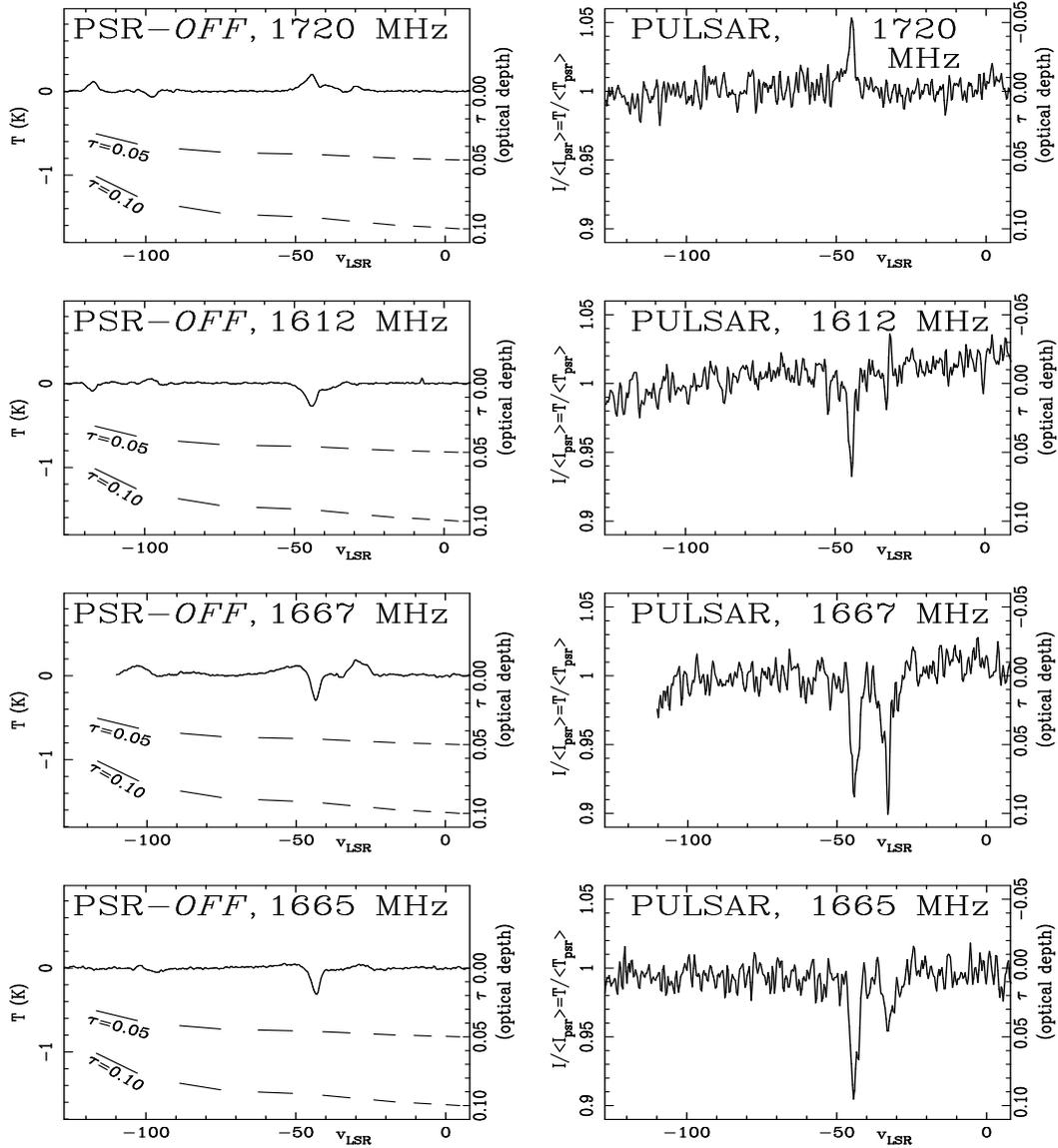
Figure 6. Pulsar-off (left) and Pulsar ISM (right) spectra at the four 18 cm OH lines toward PSR B1641-45, from Parkes observations by Weisberg et al. (2005). All spectra are plotted with the same optical depth scale. Compare pulsar-off and pulsar ISM optical depths, and also note the pulsed interstellar OH maser stimulated by the pulsar at 1720 MHz.

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