Discovery of Pulsed OH Maser Emission Stimulated by a Pulsar

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Stimulated emission of radiation has not been directly observed in astrophysical situations up to this time. Here we demonstrate that photons from pulsar B1641−45 stimulate pulses of excess 1720 MHz line emission in an interstellar OH cloud. As this stimulated emission is driven by the pulsar, it varies on a few millisecond timescale, orders of magnitude shorter than the quickest OH maser variations previously detected.

Our 1612 MHz spectra are inverted copies of the 1720 MHz spectra. This “conjugate line” phenomenon enables us to constrain the properties of the interstellar OH line-producing gas.

We also show that pulsar signals suffer significantly deeper OH absorption than do other background sources; confirming earlier tentative findings that OH clouds are clumpier on small scales than neutral hydrogen clouds.

Pulsars have proved to be outstanding tools for study of the interstellar medium. Their pulsed signals suffer a variety of modifications as they propagate through the interstellar medium (ISM), revealing extensive information about the global distribution and physical properties of the intervening material. The tiny sizes of pulsars ensure that their signals probe very small transverse scales in the ISM (1,2). Another virtue of pulsar ISM measurements is that the pulsar cycles rapidly on and off so that observations may be made contemporaneously in both the
presence and absence of the pulse, and the properties of the medium can be precisely compared in these two states. For example, comparison of neutral hydrogen (HI) spectra acquired during and between pulses leads to pulsar absorption spectra that can be used for kinematic distance and interstellar electron density determinations (3-5). Recently, Stanimirovic et al. (6) extended the pulsar spectral technique to the hydroxyl (OH) molecule with the first successful OH absorption measurements, toward PSR B1849+00. In this paper, we expand OH spectral measurements to eighteen additional pulsars, chosen because they are relatively bright and lie in the inner Galaxy near the galactic plane. One of them, PSR J1644−4559 = B1641−45, exhibits not only intervening OH absorption at 1612, 1665, and 1667 MHz, but also interstellar stimulated emission at 1720 MHz.

The widths and strengths of spectral lines from some interstellar molecules provide abundant indirect evidence for stimulated emission processes; indeed it was recognized soon after the discovery of interstellar OH in the 1960s that maser processes must be involved (7-9). Beam-switched OH measurements toward 3C123 have also demonstrated that a background source can stimulate emission in interstellar OH (10). The pulsed 1720 MHz maser detection reported here represents direct astronomical observation of the process of the radiative stimulation of emission. Here the broadband pulsar spectrum exhibits excess line emission at 1720 MHz as the pulsar’s photons stimulate the creation of additional photons in an intervening OH cloud. This excess emission switches on and off with the pulsar, clearly demonstrating its stimulated nature. In this report, we analyze these pulsar absorption and stimulated emission observations and we compare them with similar measurements in non–pulsar observations to study the physical properties of the intervening medium.

A pulsar binning spectrometer was employed to ultimately create two separate spectra: a “pulsar” spectrum and a “pulsar-off” spectrum. (See supporting online materials (11) for additional details.) The pulsar spectrum represents the signal of the pulsar alone, as absorbed or amplified by intervening OH. In contrast, the pulsar-off spectrum is sensitive to OH emission or absorption occurring anywhere within the telescope beam. The “main” OH lines at 1665 and 1667 MHz were simultaneously observed in the 4 MHz bandpass with several-hour integrations for each of the 18 pulsars in our sample. (See Table 1 for total integration times and for 1−σ optical depth uncertainties in the Hanning smoothed pulsar spectra.) After our success in detecting absorption in the 1665 and 1667 MHz pulsar spectra of PSR B1641−45, we also measured the “satellite” (1612 and 1720 MHz) lines toward the pulsar.

In order to calculate the optical depth τ of absorption or stimulated emission, consider the defining equation for optical depth: \( I/I_o = e^{-\tau} \), where \( I_o \) is the original intensity and \( I \) is the intensity after traversal through optical depth \( \tau \) of material. The differencing procedure leading to the pulsar spectrum automatically eliminates all non–pulsar signals and yields the spectrum in units of \( (I/I_o)|_{PSR} \), so it is straightforward to calibrate the pulsar spectrum in terms of \( \tau \). It is not so simple to determine optical depths in the pulsar-off spectra for several reasons. First, it is not clear whether the background emission and foreground absorption/amplification regions subtend the same solid angle. It is probably reasonable to assume in our case that the background fills the telescope beam since its predominant source is the smoothly distributed...
galactic nonthermal emission, but the size of the foreground clouds is unknown from our measurements. Consequently in the absence of better information, we will assume that both foreground and background fill the beam, so that \( I/I_0 = T/T_0 \). However, another difficulty is that the observed continuum is emitted throughout the line of sight across the Galaxy, whereas the definition of \( \tau \) requires that \( T_0 \) be only that portion emitted beyond the cloud contributing to optical depth. In order to estimate the fraction of the continuum \( f(d) \) contributing to \( T_0 \) as a function of distance \( d \), we synthesized a model of the continuum emission along the line of sight, consisting of galactic synchrotron (12), ionized hydrogen regions, and the 2.7 K Cosmic Background Radiation. We then integrated this model along the appropriate (background) part of the line of sight, and normalized the result by the total emission along the line of sight:

\[
f(d) = \frac{\epsilon_{\text{background}}}{\epsilon_{\text{tot}}} = \frac{\int_{d}^{\infty} \epsilon(s) ds}{\int_{0}^{\infty} \epsilon(s) ds} .
\]

Then \( T_0(d) = T_b f(d) \), where \( T_b \) is the brightness temperature, determined as described in supporting online materials (11). Distance was then mapped to radial velocity of the spectra with a galactic rotation model (13).

Fig. 1 displays the 1720 MHz spectra toward PSR B1641−45 which directly demonstrate the process of stimulated emission. The pulsar-off (Fig. 1a, bottom) spectrum, acquired in the interval between pulses, shows both emission and absorption against other background source(s) lying within the 13 arcmin telescope beam. The pulsar-on (Fig. 1a, top) spectrum appears to zeroth order to be merely a copy of the pulsar-off spectrum, shifted upward by a constant equal to the broadband pulsar signal strength. However, when these two spectra are carefully differenced (11) to create the pulsar spectrum (Fig. 1b), it is clear that there is excess signal at \( v \sim -45 \) km/s, where the broadband pulsar signal has been amplified by stimulated emission. It has long been thought that stimulated emission plays an important role in astrophysical OH line radiation. For example, line temperatures are frequently far in excess of those inferred from (assumed thermal) line widths (7-9). However, our measurements directly demonstrate the stimulated amplification of a signal propagating through the interstellar medium, in that the amplification is directly observable as the pulsar cycles on and off during its 455 ms rotational period. As the stimulated emission switches on and off synchronously with the pulsar pulse, our 14 ms time resolution \( \left[ \frac{1}{32} \text{ of the pulse period (14)} \right] \) places an amazingly short upper limit on its duration. Since the shortest intrinsic fluctuation timescale previously reported was \( \sim 1000 \) sec (15), these variations are by far the quickest observed in any interstellar maser.

Two conditions must be satisfied in order that stimulated emission occur: First, the relevant level populations must be inverted or “pumped” by some process; and second, appropriate photons should be available to stimulate the emission from the upper, overpopulated level. In our case, the level inversion is accomplished locally in the OH cloud by a low-energy radiative or collisional process, while the stimulating photons are provided by the pulsar.

Note that the pulsed maser line optical depth \( \tau \sim -0.05 \), implying that approximately five excess line photons are stimulated in the cloud for every hundred passing through it. As the maser is unsaturated with a gain of only 1.05, we expect that the FWHM of the line should
be very similar to the expected thermal line width, which is about 0.5–0.7 km/s for gas with kinetic temperature of 100–200 K. For example, a typical FWHM of 0.5 km/s was found in a large survey of 1720 MHz masers in star-forming regions (16). The FWHM we measure is about 2 km/s, slightly wider and suggesting that we are most likely seeing a blend of several maser spots along the line-of-sight.

It has been suggested (17) that extraterrestrial civilizations could use interstellar masers to amplify their radio transmissions. We have demonstrated here that such a process could sustain modulation down to millisecond timescales, but of course the gain of this particular maser is too small to provide significant amplification of an ETI signal.

PSR B1641–45 = J1644–4559 lies in a well–studied (18-22) region of the inner Galaxy near the galactic plane, at galactic longitude $l$ and latitude $b = (339.2^\circ, -0.2^\circ)$. We are able to construct a schematic map of the interstellar medium along the line of sight by combining our observations with earlier ones (see Fig. 2).

On the basis of kinematic analysis of HI absorption spectra (23), the pulsar is placed 4.6 kpc along the line of sight. Two ionized hydrogen (HII) regions lie in this direction, with galactic coordinates and recombination line velocities (19,20) of $(l, b, v_{\text{LSR}}) = (339.1^\circ, -0.2^\circ, -120 \text{ km/s})$ and $(339.1^\circ, -0.4^\circ, -37 \text{ km/s})$. With the rotation curve of (J3), our kinematic analysis of the recombination line measurements places G339.1–0.2 beyond the pulsar at a geocentric distance $d \sim 6.7$ kpc, and G339.1–0.4 closer than the pulsar at $d \sim 3.3$ kpc.

Fig. 3 displays spectra at frequencies of the four ground rotational state 18 cm OH lines toward PSR B1641–45. The most interesting feature is a strong spectral line at $v_{\text{LSR}} \sim -45$ km/s in all our OH spectra – both pulsar-off and pulsar spectra. The line is in absorption at 1612, 1667, and 1665 MHz and in emission at 1720 MHz (the latter being the pulsed maser emission discussed above). As it is visible in the pulsar spectra (right column, Fig. 3), this line must arise between the pulsar and the observer. It probably originates in OH gas associated with or near G339.1–0.4, as the velocities are similar. Note however that pervasive extended regions of 1720 MHz emission have been found in the inner galactic plane (24,25), including a > 1°–long filament crossing near the pulsar line of sight with $v_{\text{LSR}} \sim -40$ km/s. As our 1720 MHz pulsar-off spectral line at $-45$ km/s has strength and width similar to the extended OH gas (though the velocities are somewhat discrepant), it is possible that it originates from this extended OH region rather than from the HII region G339.1–0.4.

The $-45$ km/s emission and absorption features show evidence for departures from local thermodynamic equilibrium (LTE). The pulsar-off spectra typically have FWHM of 2-3 km/s, which is a few times wider than what is expected for thermally broadened line profiles at a typical kinetic temperature of about 100 K. The peak optical depths are very similar at 1667 and 1665 MHz ($\tau \sim 0.03$), while in the LTE case their ratio would be 9/5. In addition, the 1612 MHz lines are inverted with respect to 1720 MHz.

We see another OH line at $v_{\text{LSR}} \sim -30$ km/s in most of the eight spectra toward PSR B1641–45 shown in Fig. 3, including the 1665 and 1667 MHz pulsar spectra. This line must therefore also originate in gas nearer than the pulsar to us, again probably associated with or near G339.1–0.4. The lines are seen in absorption in pulsar spectra and primarily in emission
in pulsar-off spectra.

Finally, all pulsar-off spectra exhibit line(s) at \( v_{\text{LSR}} \sim -100 \) to \(-120 \) km/s, which are not seen in the pulsar spectra. Consequently they must originate in gas beyond the pulsar, probably associated with or near G339.1–0.2.

Note that each 1720 MHz spectrum (Fig. 3, top row) is an inverted copy of the 1612 MHz spectrum (Fig. 3, second row). This phenomenon, called “conjugate” line behavior, occurs because the initial states of both transitions are overpopulated by an identical process (8,26-28). For our predominantly observed conjugate state, having 1720 MHz stimulated emission and 1612 MHz stimulated absorption, the process begins in a region having \( T \sim 100 \) K and \( n_{\text{OH}} \sim 10^5 \) cm\(^{-3}\) with the collisional excitation of the molecule to a higher rotational state at energy \( E = 1.66 \times 10^{-14} \) erg above ground level, after which it can radiatively decay with equal probability (if the transition is optically thick) to overpopulate either the upper level of the 1720 MHz transition or the lower level of the 1612 MHz transition. The rarer (in our data) 1612 MHz stimulated emission and conjugate 1720 MHz stimulated absorption results from a similar process that overpopulates the opposite 18 cm levels via an intermediate excited rotational level at \( E = 2.5 \times 10^{-14} \) erg above the ground level.

Our predominant conjugate configuration becomes optically thick to far-infrared photons for OH column densities per velocity interval \( (N_{\text{OH}}/\Delta v) > (10^{14} \) cm\(^{-2}\) s / km), whereas the inverse configuration becomes optically thick and then dominates at \( (N_{\text{OH}}/\Delta v) > (10^{15} \) cm\(^{-2}\) s / km). Hence our predominant conjugate configuration (including the 1720 MHz pulsar-stimulated emission and the pulsar-off emission at \( v \sim -120 \) km/s) originates in clouds with specific column densities between these two limits, while the rarer opposite configuration (e.g., pulsar-off 1720 MHz absorption at \( v \sim -100 \) km/s) originates in a column whose density is above the upper limit. Then the occasionally observed adjacent emission and absorption features that are conjugate at the two frequencies (e.g., the pulsar-off spectra at \( v \sim -32 \) km/s) suggest a density gradient in the cloud (28), with specific column densities crossing \( (10^{15} \) cm\(^{-2}\) s / km) at the transition.

It is useful to compare the lines observed in the pulsar and pulsar-off spectra, since all were acquired at the same time with the telescope pointing in exactly the same direction. To facilitate the comparison, optical depth scales on the right side of all eight spectra in Fig. 3 are identical. The \( v \sim -45 \) km/s lines exhibit markedly stronger \( (|\tau| \sim (2 - 3)\times \) larger) absorption and stimulated emission in pulsar spectra (Fig. 3, right column) than in the corresponding pulsar-off spectra (Fig. 3, left column). The discrepancy at \( v \sim -32 \) km/s is even stronger – absorption in pulsar spectra at 1665 and 1667 MHz is absent or replaced by weak emission in pulsar-off spectra (29). These results are striking, especially since the only other successful pulsar OH absorption experiment (6) also found stronger absorption in the pulsar spectra than in the pulsar-off spectra.

The widths of the lines are narrower in our pulsar spectra than in pulsar-off spectra at 1720 and 1612 MHz, but similar at 1667 and 1665 MHz. The earlier results (6) exhibited narrower lines in the pulsar spectra than in the pulsar-off spectra at 1667 and 1665 MHz.

Our new observations strengthen the earlier interpretation that the needle–thin interstel-
lar column sampled by the pulsar signal interacts with a substantially different sample of the medium than does the pulsar-off column, which represents the average of all interactions across the 13 arcmin telescope beam. Presumably the pulsar signal is encountering small, dense OH cloudlets whose properties are diluted in the beam–averaged pulsar-off spectrum. This behavior differs markedly from HI, where the statistics show no dependence on the angular cross-sections of absorbing columns across a tremendous range of solid angle (30,31). Interestingly, molecular gas is known to be more clumped than neutral gas, at least on larger scales.

If the difference in OH optical depths indeed results from clumping, we would expect that other pulsar lines of sight would pierce regions devoid of cloudlets and show shallower optical depths than pulsar-off measurements. One might ask why there are no such complementary results. Unfortunately an observational selection effect conspires against success in such observations, as we do not have sufficient sensitivity on any other pulsar lines of sight (see Table 1) to test this hypothesis.

An earlier paper (32) reported broad ($\Delta v > 10$ km/s) and deep ($\tau > 0.5$) OH absorption at 1667 MHz in the spectrum of PSR B1749−28. We have adequate sensitivity to detect such a line (see Table 1), but we do not confirm the result. All other OH lines detected in pulsar spectra are much narrower than the previously claimed detection in PSR B1749−28.

We have searched for OH absorption and stimulated emission in the spectrum of 18 pulsars. One pulsar, B1641−45, exhibits absorption or stimulated emission in pulsar spectra at each of the four 18 cm line frequencies. No absorption or stimulated emission was detected in the others, including one in which OH absorption had previously been reported (B1749−28). A variety of interesting results are drawn from the B1641−45 spectra. The pulsed maser line, with $\tau \sim -0.05$, represents the first direct detection of interstellar stimulated emission. The OH and HII concentrations are mapped along the line of sight to the pulsar, and they are found to be associated kinematically and probably spatially. Analysis of the lines provides insight into the OH density, temperature, and excitation. Finally, the relative depths of lines in pulsar spectra and pulsar-off spectra suggest that the OH gas is highly clumped.

**Supporting online material: Methods**

The observations reported here were obtained with the 64-m telescope located near Parkes, NSW, Australia, in September 2004, with the H-OH front-end receiver package. At our 18-cm observing wavelength, the telescope has a sensitivity of 1.5 Jy/K and a beam diameter of 13 arcmin. The back–end correlation spectrometer was used in the pulsar binning mode, in which each correlation function was integrated into one of thirty–two pulse phase bins. Each of the 32 resulting spectra covered a 4 MHz band that was divided into 2048 spectral channels, each $\sim 2$ kHz or $\sim 0.4$ km/s wide. The spectra acquired in the phase bins corresponding to the pulsar pulse were collapsed into a single pulsar-on spectrum; while the spectra gathered in the interval between pulses were integrated into a single pulsar-off spectrum. The pulsar spectrum was formed from differencing pulsar-on and pulsar-off spectra, and normalizing by the mean pulsar
temperature. No additional baseline flattening is required in the pulsar spectrum, while low-
order sinusoids were fitted to and removed from the final pulsar-off spectrum. Lastly, all spectra
were Hanning smoothed, giving a final resolution of $\sim 0.7$ km/s. We have previously used
similar pulsar binning spectrometric techniques for HI measurements at Parkes and Arecibo
observatories (I-5), and for OH at Arecibo (6).

The data were calibrated using observations of Hydra A, whose flux density near 1660 MHz
was assumed to be 36.8 Jy. The system temperature $T_{\text{sys}}$ was found to be 28.7 and 29.9 K in
the two linearly polarized feed probes. An additional contribution from the sky at the pulsar
position was estimated by convolving a 1400-MHz interferometric image (22) with a 13 arcmin
beam and then extrapolating the resultant brightness temperature (less contributions from the
Cosmic Background Radiation and HII regions) to 1650 MHz with a spectral index of -2.7.
Line brightness temperatures were then determined under the assumption that the line-emitting
regions fill the telescope beam, by measurement of the line-to-total continuum ratio.

References and Notes

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33. The quantity $\sigma_\tau$ (pulsar spectrum) in Table 1 is the optical depth standard deviation in the Hanning smoothed pulsar spectrum, which includes the effects of radiometer and sky noise, and in some cases, interstellar scintillation.

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**Table 1**: Integration times and pulsar spectrum noise fluctuations.

| PSR J     | PSR B     | Freq (MHz) | $t_{tot}$ (hr) | $\sigma_\tau$ (33) (pulsar spectrum) |
|-----------|-----------|------------|---------------|------------------------------------|
| 0742–2822 | 0740–28   | 1665/7     | 3             | 0.1                                 |
| 0835–4510 | 0833–45   | 1665/7     | 2             | 0.1                                 |
| 0837–4135 | 0835–41   | 1665/7     | 4             | 0.07                                |
| 0908–4913 | 0906–49   | 1665/7     | 4             | 0.1                                 |
| 1056–6258 | 1054–62   | 1665/7     | 2             | 0.1                                 |
| 1057–5226 | 1055–52   | 1665/7     | 1             | 0.1                                 |
| 1157–6224 | 1154–62   | 1665/7     | 2             | 0.3                                 |
| 1243–6423 | 1240–64   | 1665/7     | 2             | 0.1                                 |
| 1326–5859 | 1323–58   | 1665/7     | 2             | 0.1                                 |
| 1327–6222 | 1323–62   | 1665/7     | 2             | 0.1                                 |
| 1600–5044 | 1557–50   | 1665/7     | 7             | 0.1                                 |
| 1605–5257 | 1601–52   | 1665/7     | 1             | 0.2                                 |
| 1644–4559 | 1641–45   | 1665/7     | 5             | 0.01                                |
| “ “ “ “  | “ “ “ “  | 1720       | 5             | 0.01                                |
| “ “ “ “  | “ “ “ “  | 1612       | 4             | 0.01                                |
| 1745–3040 | 1742–30   | 1665/7     | 5             | 0.2                                 |
| 1752–2806 | 1749–28   | 1665/7     | 4             | 0.05                                |
| 1803–2137 | 1800–21   | 1665/7     | 5             | 0.3                                 |
| 1825–0935 | 1822–09   | 1665/7     | 1             | 0.3                                 |
| 1829–1751 | 1826–17   | 1665/7     | 2             | 0.3                                 |
Figure 1: Stimulated amplification of the PSR B1641−45 signal in an interstellar OH cloud at 1720 MHz. (a). The “pulsar-on”spectrum, acquired during the pulsar pulse, and the “pulsar-off” spectrum, gathered in the interval between pulses. The two spectra exhibit both emission and absorption against other (non–pulsar) background source(s) lying within the 13 arcmin telescope beam, while the pulsar-on spectrum additionally contains the pulsar signal. (b). The “pulsar” spectrum, the difference of pulsar-on and pulsar-off, illustrating the pulsar signal alone as absorbed (or in this case, amplified) by intervening OH. The spike in this spectrum at $v_{\text{LSR}} \sim -45$ km/s results from excess emission in an OH cloud, stimulated by pulsar photons.
Figure 2: A schematic model of the ISM toward PSR B1641−45. The ionized region velocities are from (19, 20), the OH velocities are from the current work, and the limiting pulsar HI absorption velocities are from (23). The kinematic velocity–to–distance conversion uses the rotation curve of (13). The lines represent various lines of sight within the 13 arcmin telescope beam. The vertical scale has been enlarged for clarity.
Figure 3: Spectra of the four 18 cm ground–state rotational transitions of OH toward PSR B1641-45. The left column displays the four "pulsar-off" spectra, which are sensitive to all emission and absorption in the 13 arcmin telescope beam when the pulsar is switched off. The right column shows the four "pulsar" spectra, which exhibit the absorption or stimulated emission of the pulsar signal alone. The right-hand ordinate on each panel is optical depth $\tau$; all eight spectra are plotted with the same optical depth scale. Note that all pulsar-off spectral features are significantly shallower (i.e., have smaller optical depths) than their analogs in the pulsar spectra. In the pulsar-off spectra, the sloping lines of constant optical depth result from changes in the ratio of background to total continuum along the line of sight (see discussion accompanying Eq. 1). Low-order sinusoids were fitted to and removed from the pulsar-off baselines in order to flatten them.