Intrinsic Sizes of the W3 (OH) Masers via Short Time Scale Variability

Tanmoy Laskar[1], W. M. Goss[2] and B. Ashley Zauderer[1]

[1]Harvard University, 60 Garden St., Cambridge, MA - 02138, USA
email: `tlaskar@cfa.harvard.edu`

[2]National Radio Astronomy Observatory, PO Box 0, Socorro, NM - 87801, USA
textitail: `mgoss@aoc.nrao.edu`

Abstract. We present a study of short time-scale variability of OH masers within a contiguous 15-hour Very Long Baseline Array observation of the high-mass star-forming region, W3 (OH). With an angular resolution of ~ 7 mas and a velocity resolution of $53\,\mathrm{m\,s^{-1}}$, we isolate emission from masers in the field into individual Gaussian-shaped components, each a few milliarcseconds in size. We compute dynamic spectra for individual maser features with a time resolution of 1 minute by fitting for the flux density of all sources in the field simultaneously in the uv-domain. We isolate intrinsic maser variability from interstellar scintillation and instrumental effects. We find fluctuations in the maser line shape on time scales of 5 to 20 minutes, corresponding to maser column lengths of 0.5 to 2.0 Astronomical Units.

1. Introduction

Galactic OH masers have been found to be variable on a variety of time scales: from years (Caswell & Vaile 1995) and months (e.g., Slysh *et al.* 2010) to days (Clegg & Cordes 1991). The origin of this long-time scale variability is unknown, although proposed mechanisms have included changes in the physical conditions of the maser column (e.g., Zuckerman *et al.* 1972), sudden onset of pumping (Salem & Middleton 1978), and radiative instabilities in the maser column (Scappaticci & Watson 1992). Maser variability studies on time scales on the order of minutes are useful in probing the length of the maser column. Such studies have proved challenging, in part due to the effects of interstellar diffractive scintillation and the need to study spectrally-isolated masers.

Recently, Ramachandran *et al.* 2006 (hereafter R06) studied variability in the galactic star-forming region, W3(OH) on short ($\sim$ minute) timescales with archival VLBA data (Wright *et al.* 2004). They employed a statistical technique to separate the effects of interstellar diffractive scintillation, based on the expectation for variability arising from scintillation to have a wider correlation bandwidth compared to the maser line width. After accounting for scintillation, they found significant residual variability (modulation indices up to 100%) on time scales of about 15-20 minutes in the line wings of three strong, spectrally-isolated masers at 1612, 1665 and 1720 MHz. Although this provided tantalizing evidence for intrinsic variability of OH masers, certain aspects of the data used made it unfavorable for a final and conclusive analysis: the data had non-uniformly spaced gaps whenever a calibrator was observed, making standard Fourier analysis on the time series difficult. Additionally, the velocity resolution of $90\,\mathrm{m\,s^{-1}}$ resulted in spectral blending, making it hard to find isolated maser sources for variability analysis.

We present the results of a variability study of OH masers in W3(OH) using Very Long Baseline Array (VLBA) data obtained with a factor of 2 better velocity resolution compared to the data used by R06. We fit for all maser sources present in the field
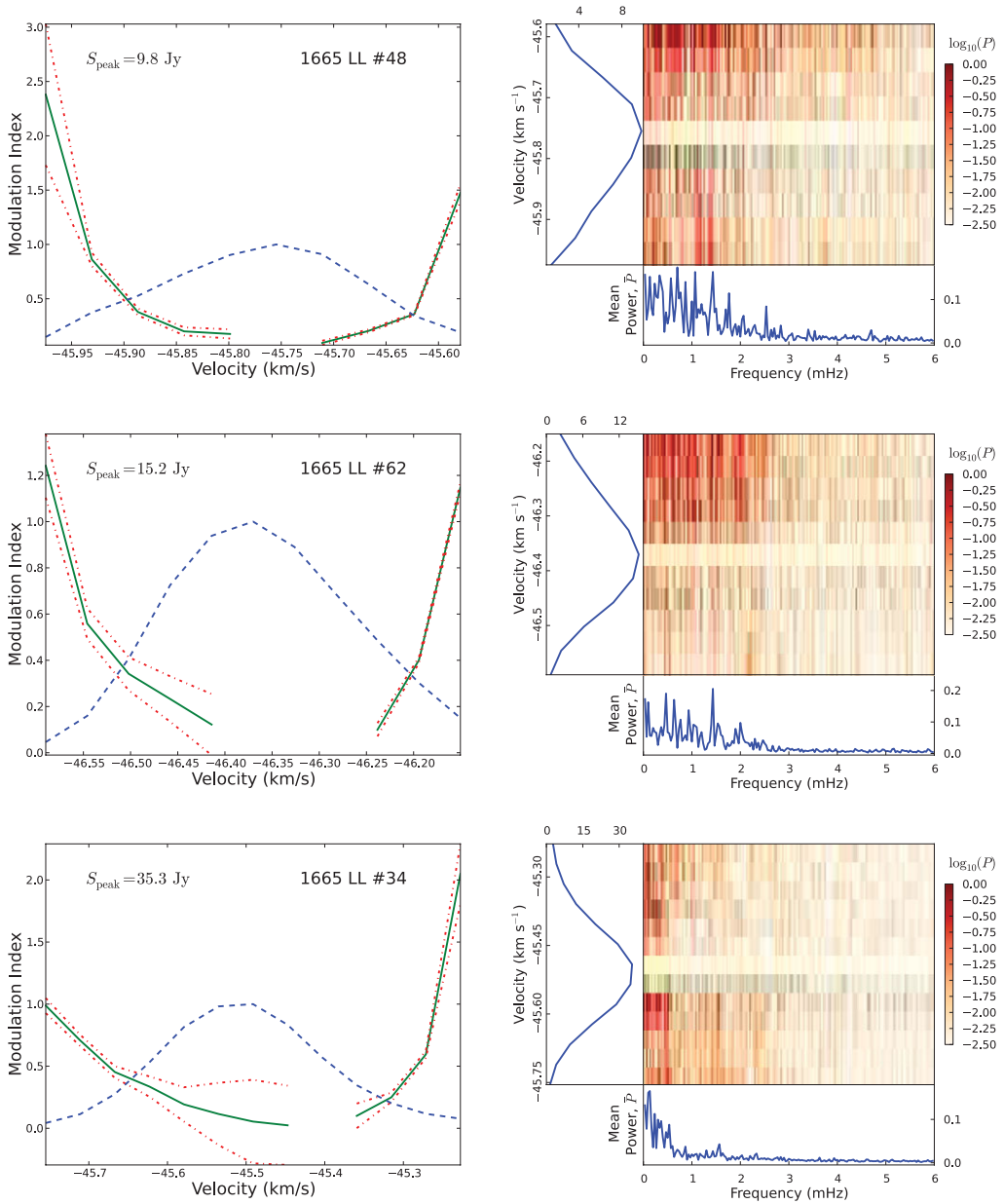
Figure 1. Left: Modulation index (solid green lines) and $\pm 1\,\sigma$ uncertainties (dotted red lines), together with normalized spectral line profiles (blue dashed lines) for eight maser sources in W3(OH). The details of the masers used are presented in Table 1. All sources exhibit statistically significant variability in the line wings (modulation indices $\gtrsim 50\%$). The line core appears not to be variable in all cases, confirming the results of Ramachandran *et al.* 2006. Right: Fluctuation power spectra for each source, obtained by Fourier transforming each channel in the dynamic spectrum and taking the square modulus. In each sub-figure, the 2d frame is the velocity-resolved fluctuation spectrum in logarithmic units, the bottom panel is the velocity-averaged fluctuation spectrum in linear units, and the left panel is the average line profile in Jy/beam. The power spectra demonstrate a cut-off at high frequencies, corresponding to time scales of $5 - 20$ minutes. The 1665 MHz Stokes LL sources (arranged here in order of increasing flux density) appear to show decreasing power at high fluctuation frequencies, indicating a possible increase in the time scale of variability with flux density.
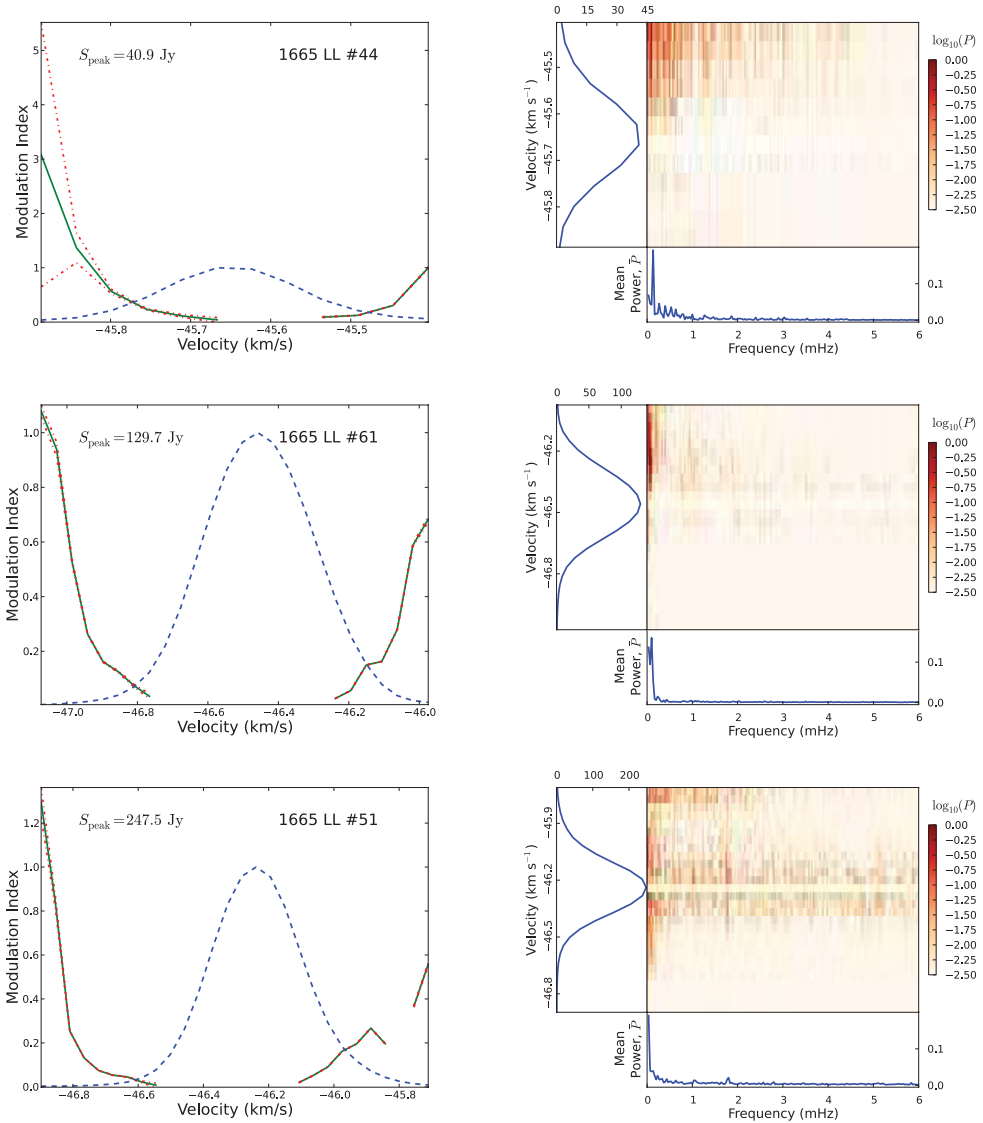
Figure 1. (Continued)

simultaneously directly in the *uv*-domain, lifting the restriction of sources under study to be spectrally isolated, which greatly increases the number of masers available for this study. Using the statistical tools of R06, we find variability on time scales of $5 \sim 20$ minutes with modulation indices between 50 and 100% for eight maser sources in W3(OH), implying maser column lengths of 0.5 to 2 astronomical units.

2. Observations and Data Analysis

We obtained a 15-hour contiguous observation of W3 (OH) with the VLBA (all ten VLBA stations) on 2005 July 07 (VLBA program BR107) in all four ground state transitions with a velocity resolution of $\sim 53\,\mathrm{m\,s^{-1}}$. RFI was excised and the data were phase self-calibrated. In $4'' \times 4''$ images (synthesized beam $6.7 \times 7.7\,\mathrm{mas}$), we detected
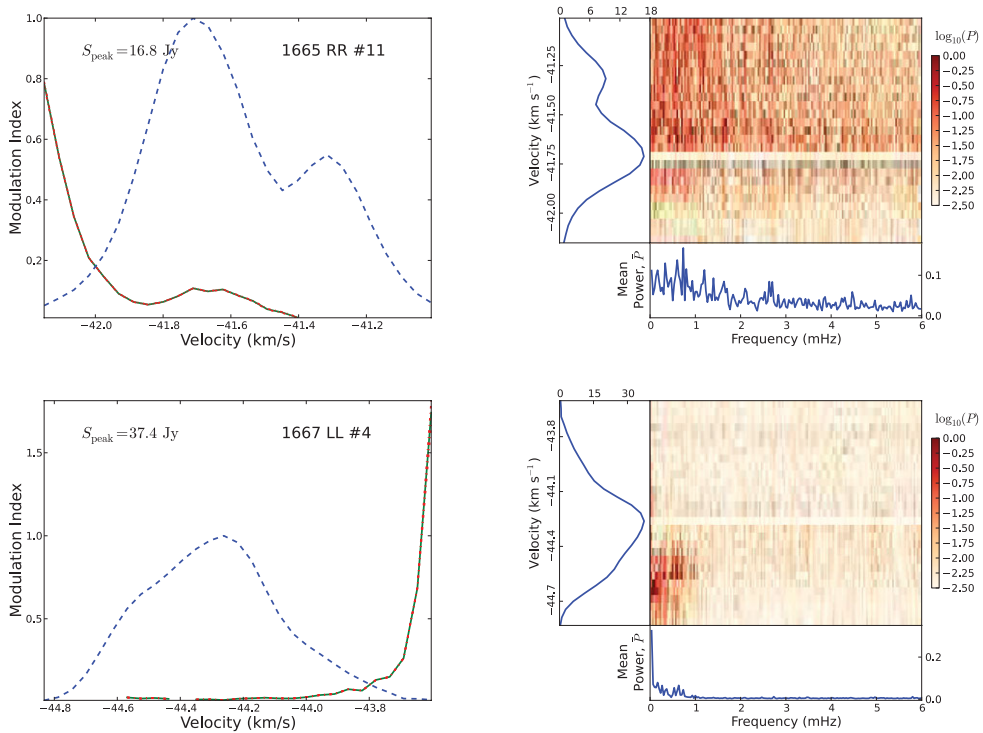
Figure 2. Similar to Figure 1, for a 1665 RR maser and a 1667 LL maser.

approximately 20 distinct maser sources at 1612 MHz, 10 at 1720 MHz, 180 at 1665 MHz and 40 at 1667 MHz brighter than 10 σ. The noise level in our maps ranged from ~ 30 mJy/beam in line-free parts of the spectrum to ~ 60 mJy/beam in channels with strong masers.

Dynamic spectra for every source brighter than 1 Jy were generated by simultaneously fitting for the flux density in the uv domain in the entire 256-channel spectral cube at 1 minute intervals. The fitting was carried out in the uv domain since the sparse uv-coverage at short integrations results in very poor image fidelity with large side-lobe responses whenever multiple sources are present in a single spectral channel, as is the case for the majority of channels in the data cube. With this simultaneous fit for all maser sources, we are not restricted to analyzing only spectrally-isolated sources and are able to extend the work by R06 to all strong sources in the entire data set. For the 1-minute fits, we fixed the positions and shape properties of each maser component to the values determined by imaging the full 15-hour observation.

We used statistical techniques from R06 to determine modulation indices across the line profile for 8 maser sources (Figure 1, left panels). These modulation indices imply significant ($\sim 100\%$) variability in the line wings. In each case, the modulation index is consistent with zero near the peak of the line, indicating that the line core is not significantly variable. Both of these results are in agreement with the conclusions of R06.

3. Fluctuation Analysis

To estimate the time scale corresponding to narrow band variability, the contribution of broad band variability to the dynamic spectrum must be removed. We achieve this by dividing the observed dynamic spectrum by the flux density in the reference channel

Table 1. List of masers used for the present analysis.

Transition (MHz)	Polarization	Source Number[1]	Velocity[2] (km s^{-1})	RA offset[3] arcsec	Dec offset[3] arcsec
1665	LL	34	-45.51	-0.595	-1.918
1665	LL	44	-45.65	-0.711	-1.673
1665	LL	48	-45.77	-0.851	-0.618
1665	LL	51	-46.24	-1.024	-0.123
1665	LL	61	-46.45	-0.960	-0.103
1665	LL	62	-46.37	-0.168	-0.044
1665	RR	11	-41.63	-0.141	-1.185
1667	LL	4	-44.31	-0.386	-1.886

*N*otes:
[1] The source numbers given here are internal to our analysis, and are likely to change in a future publication.
[2] LSR Velocity of the line centroid, determined by fitting a single Gaussian to the spectral line.
[3] Right Ascension and Declination offsets (J2000.0) from the phase center, corresponding to the location of the flux-weighted centroid of the maser line. Since our data were self-calibrated, the exact location of the phase center in RA and Dec is uncertain. Preliminary analysis suggests that our offset coordinate system is comparable (within about 10 mas) to that used by Fish *et al.* 2006.

defined by the peak of the average line profile. This is justified since the peak of the line does not exhibit statistically significant narrow band variations, as apparent from the modulation indices (Figure 1, left panels). We compute the fluctuation power spectrum for each channel by Fourier transforming the time series in each channel individually, followed by taking the square modulus. Our preliminary results are shown in Figure 1 (right panels). Excess power is evident at low frequencies, below about 3×10^{-3} Hz, corresponding to a minimum variability time scale of about 5 minutes. The power spectra for the 1665 MHz Stokes LL masers also hint at a possible decrease in power at high fluctuation frequencies (corresponding to an increase in the variability time scale), with increasing flux density of the maser line.

In summary, we confirm the results of R06 and find fluctuations in the maser line shape on time scales of 5 to 20 minutes, corresponding to maser columns of 0.5 to 2.0 AU. In a future publication, we aim to extend our analysis to other maser sources in the field and to compare variability between masers in Zeeman pairs.

References

Baudry, A., Desmurs, J. F., Wilson, T. L., & Cohen, R. J. 1997, *A&A*, 325, 255
Caswell, J. L. & Vaile R. A. 1995, *MNRAS*, 273, 328
Clegg, A. W. & Corders J. M. 1991, *ApJ*, 374, 150
Fish, V. L., Brisken W. F., & Sjouwerman L. O. 2006, *ApJ*, 647, 418
Ramachandran, R., Deshpande, A. A., & Goss, W. M. 2006, *ApJ*, 653, 1314
Rickard, L. J., Palmer, P., & Zuckerman, B. 1975, *ApJ*, 200, 6
Salem, M. & Middleton, M. S. 1978, *MNRAS*, 183, 491
Scappaticci, G. A. & Watson, W. D. 1992, *ApJ*, 400, 351
Slysh, V. I., Alakoz, A. V., & Migenes, V. 2010, *MNRAS*, 404, 1121
Wright, M. M., Gray, M. D., & Diamond, P. J. 2004, *MNRAS*, 350,1253
Zuckerman, B. Yen, J. L., Gottlieb, C. A., & Palmer, P. 1972, *ApJ*, 177, 59