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658 GHz vibrationally-excited water masers with the Submillimeter Array

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Abstract. Discovered in 1995 at the Caltech Submillimeter Observatory (CSO), the vibrationally-excited water maser line at 658 GHz (455 micron) is seen in oxygen-rich giant and supergiant stars. Because this maser can be so strong (up to thousands of Janskys), it was very helpful during the commissioning phase of the highest frequency band (620-700 GHz) of the Submillimeter Array (SMA) interferometer. From late 2002 to early 2006, brief attempts were made to search for emission from additional sources beyond the original CSO survey. These efforts have expanded the source count from 10 to 16. The maser emission appears to be quite compact spatially, as expected from theoretical considerations; thus these objects can potentially be used as atmospheric phase calibrators. Many of these objects also exhibit maser emission in the vibrationally-excited SiO maser at 215 GHz. Because both maser lines likely originate from a similar physical region, these objects can be used to test techniques of phase transfer calibration between millimeter and submillimeter bands. The 658 GHz masers will be important beacons to assess the performance of the Atacama Large Millimeter Array (ALMA) in this challenging high-frequency band.

1. Introduction

Water is an asymmetric top molecule with three vibrational quantum numbers (Herzberg 1945). The presence of vibrationally-excited water has been detected at near-IR wavelengths in a variety of astrophysical environments such as the atmospheres of Mira variable stars (e.g. R Leo, Hinkle & Barnes 1979), semi-regular pulsating stars (e.g. W Hya, Justtanont *et al.* 2004), FU Orionis objects (Reipurth *et al.* 2007), Mars (Jouglet *et al.* 2006), and in the post-Deep Impact ejecta from Comet Temple 1 (Barber *et al.* 2006). Of the three vibrational modes, the $v_2 = 1$ bending mode has the lowest energy ground state (2297 K). Rotational levels for this mode are tabulated by Camy-Peyret *et al.* (1977) and a level diagram is presented by Alcolea & Menten (1993). Frequency measurements are given by Belov *et al.* (1987), Pearson *et al.*(1991), and Chen *et al.* (2000). Analogous frequencies for deuterated water are currently being measured (Brünken *et al.* 2005).

Table 1. Astronomically-detected (sub)millimeter transitions of vibrationally-excited water

Frequency (GHz)	Rotational Transition	Vibrational State	Species	$E_{\rm upper}$ (K)	Telescope	Discovery Reference
96.261	$4_{4,0} \rightarrow 5_{3,3}$	010	para	3066	IRAM 30m	Menten & Melnick 1989
232.686	$5_{5,0} \rightarrow 6_{4,3}$	010	ortho	3465	IRAM 30m	Menten & Melnick 1989
293.664	$6_{6,1} \rightarrow 7_{5,2}$	010	ortho	2941	APEX 12m	Menten *et al.* 2006
336.227	$5_{2,3} \rightarrow 6_{1,6}$	010	ortho	2958	APEX 12m	Menten *et al.* 2006
658.006	$1_{1,0} \rightarrow 1_{0,1}$	010	ortho	2362	CSO 10.4m	Menten & Young 1995

Emission from water vapor in the $v_2 = 1$ state has been detected in astronomical sources in several (sub)millimeter lines (see Table 1). Searches have been performed for three other $v_2 = 1$ transitions with negative results: para $6_{6,0} \rightarrow 7_{5,3}$ at 297.439 GHz (Menten *et al.* 2006), ortho $4_{2,3} \rightarrow 3_{3,0}$ at 12.008 GHz (Myers & Barrett 1982), and ortho $4_{1,4} \rightarrow 3_{2,1}$ at 67.704 GHz (Petuchowski & Bennett 1991). All of the lines in Table 1 have been detected in the hypergiant star VY CMa. With the exception of the 336 GHz line, all of the detected lines in this object show evidence for maser action, at least in some velocity components. The 232 GHz line is also seen in the semi-regular pulsating star W Hya. The 658 GHz transition to the ortho ground state is seen as a strong maser in both objects, along with eight other evolved stars including three semi-regular stars (R Crt, RT Vir, RX Boo), two hypergiants (VX Sgr, NML Cyg) and three Miras (R Leo, S CrB, U Her). Unlike the non-vibrational water lines at 22 GHz, 183 GHz (Cernicharo *et al.* 1990), 321 GHz (Menten *et al.* 1990a), 325 GHz (Menten *et al.* 1990b), 439 and 470 GHz (Melnick *et al.* 1993), the 658 GHz line is not detected as a maser in star-forming regions. However, the 658 GHz line is detected as a thermal line in the CSO Orion KL 600-720 GHz line survey (Schilke *et al.* 2001). In this paper, we describe the first $1'' - 2''$ resolution observations of the 658 GHz maser and present new detections from six additional Mira variables obtained by the Submillimeter Array (SMA)†.

2. Observations

Summarized in Table 2, the SMA observations were performed primarily during commissioning periods of the 600 GHz receivers and their associated IF path (Hunter *et al.* 2002). The SMA receivers are double sideband (DSB), fixed-tuned SIS mixers with an IF output band of 4-6 GHz. Further description of the SMA antennas and receivers can be found elsewhere (Blundell 2004). Prior to January 2005, SMA observations could only be obtained in one receiver band at a time. As of January 2005, simultaneous observations of the same target position with two receiver bands could be obtained: (200 GHz with 600 GHz) or (300 GHz with 600 GHz). During the observations, in most cases the 200 GHz band was tuned to the SiO v =1, J =5-4 maser line at 215 GHz in lower sideband (LSB). The 658 line was typically tuned in upper sideband (USB). The H_2O maser line was observed with a correlator channel spacing of 0.8125 MHz (0.4 km/s). The compact configuration was used, with baseline lengths ranging from 16 to 69 meters. Callisto was the flux calibrator.

Table 2. Log of significant SMA observations in the 658 GHz water maser line

Date	Log #	Antennas	$\tau_{225\mathrm{GHz,zenith}}$	New detections	Other detections‡
12 Dec 2002	4327	3	0.03 - 0.05	U Ori	
08 Apr 2004	7082	4	0.07	R Cas, R Aql	VY CMa, U Her, R Leo & W Hya
24 Jan 2005	8690	5	0.06		W Hya
28 Jan 2005	8726	5	0.06		R Leo, VY CMa
16 Feb 2005	8847	6	0.03 - 0.06		VY CMa
24 Aug 2005	9962	7	0.05 - 0.08		VX Sgr
14 Dec 2005	10802	7	0.028	TX Cam, NML Tau	R Cas
11 Jan 2006	10721	6	0.06	R Hya	VY CMa, R Leo

‡Non-detections: IRC+10011, Betelgeuse, IRC+70066, GX Mon, OH231.8+4.2, RS Cnc

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† Located on Mauna Kea, Hawaii, the Submillimeter Array (SMA) is an eight-element interferometer built and operated as a collaborative project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy & Astrophysics of Taiwan.

3. Results

3.1. *New detections*

With the SMA, new detections were obtained of six Mira variables. As an example, calibrated uv spectra of R Cas and R Aql are shown in Fig. 1.

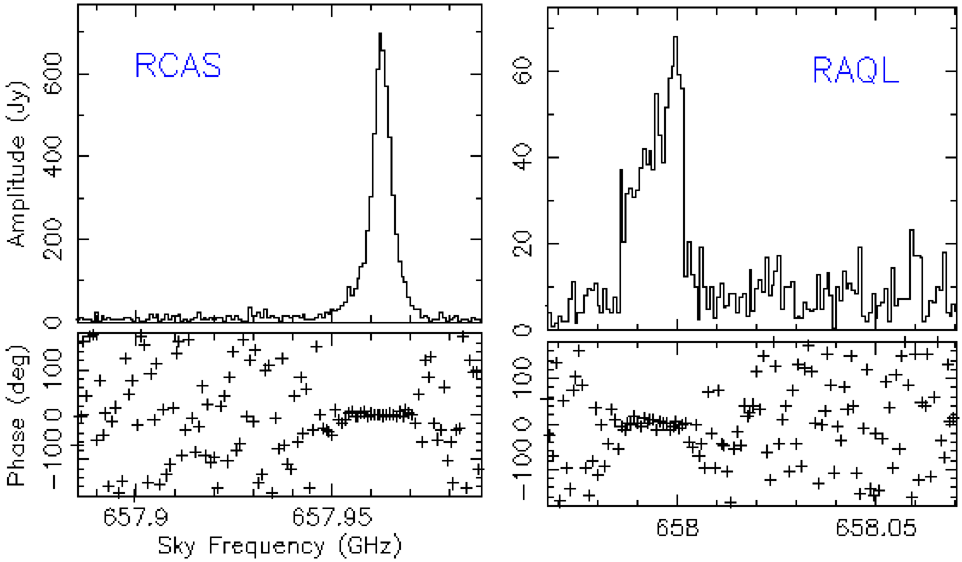

Figure 1. Calibrated SMA uv spectra of the Mira variables R Cas (left panel) and R Aql (right panel) in the 658 GHz H_2O maser line. The velocity range shown is 47 km/s (104 MHz).

These detections increase the total number of objects detected in this maser line either by CSO or SMA from 10 to 16. A complete listing of objects that have been detected in this line is given in Table 3.

Table 3. List of all objects detected in the 658 GHz water maser line (as of March 2007)

Object		Position†		Spectral	Distance	Velocity
Class	Name	α (J2000)	δ (J2000)	Type	(pc)	km/s
semi-regular pulsating stars	R Crt	11 00 33.85	−18 19 29.6	M7III, SRb	186‡	8
	RT Vir	13 02 37.98	+05 11 08.4	M8III, SRb	220	15
	W Hya	13 49 02.00	−28 22 03.5	M7e, SRa	98	42
	RX Boo	14 24 11.63	+25 42 13.4	M7.5, SRb	141‡	1
hypergiants	VY CMa	07 22 58.33	−25 46 03.2	M3/M4II	1500¶	22
	VX Sgr	18 08 04.05	−22 13 26.6	M5/M6III, SRc	1400	7
	NML Cyg	20 46 25.46	+40 06 59.6	M6IIIe	2000	−1
Mira variables	NML Tau	03 53 28.84	+11 24 22.6	M6me	270	32
	TX Cam	05 00 50.39	+56 10 52.6	M8.5	380	9
	U Ori	05 55 49.17	+20 10 30.7	M8III	256	39
	R Leo	09 47 33.49	+11 25 43.6	M8IIIe	110	0
	R Hya	13 29 42.78	−23 16 52.8	M7IIIe	125	−11
	S CrB	15 21 23.96	+31 22 02.6	M7e	430	1
	U Her	16 25 47.47	+18 53 32.9	M7III	347‡	−15
	R Aql	19 06 22.25	+08 13 48.0	M7IIIev	220	48
	R Cas	23 58 24.87	+51 23 19.7	M7IIIe	184‡	26

†ICRS positions taken from SIMBAD ‡Colomer *et al.* (2000) ¶Lada & Reid (1978)

3.2. *Comparison of H_2O and SiO maser line widths*

A comparison of the simultaneous spectral observations of the 658 GHz water maser with the 215 GHz SiO $v = 1$ maser in four objects is shown in Fig. 2. The emission from these two species arises from a similar range of velocities, which has been interpreted as evidence for a common physical origin (Menten & Young 1995), particularly because the lower level of the SiO $v = 1$ maser lies at a similar energy above the ground state (1792 K) as does the 658 GHz line. A scatter plot of the line width (FWZI) of these two masers in all 16 objects is shown in Fig. 3.

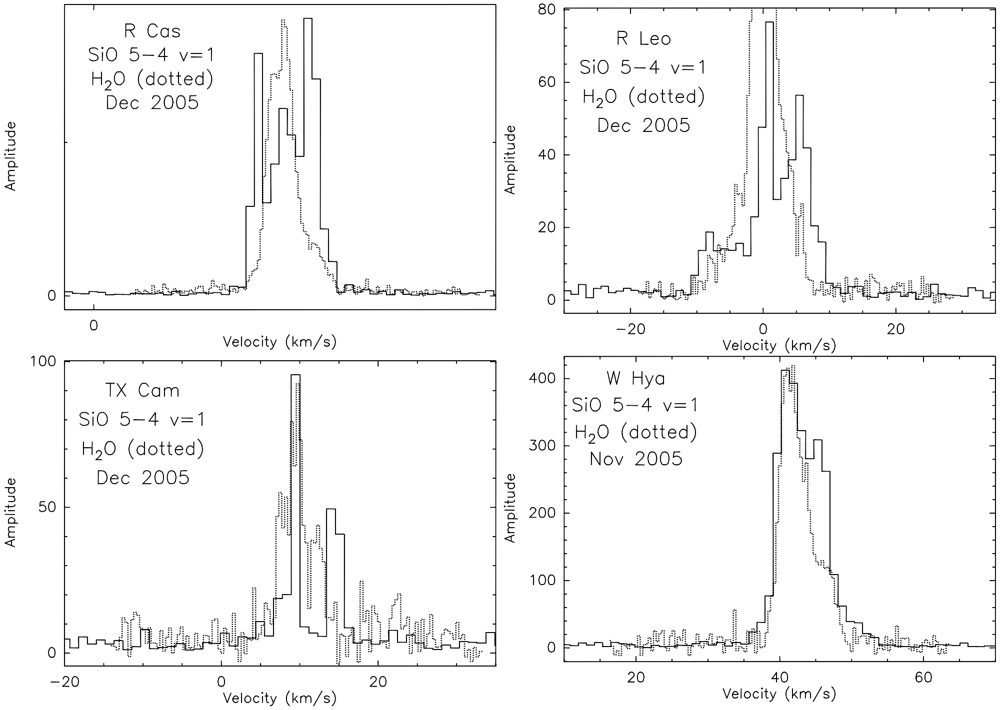

Figure 2. Simultaneous SMA uv spectra of SiO J =5-4, $v = 1$ (solid line) and 658 GHz H_2O (dotted line) in four evolved stars. The channel spacing was 3.25 MHz (4.5 km/s) for SiO, and 0.8125 MHz (0.4 km/s) for H_2O.

3.3. *Source size*

To investigate the source size of the 658 GHz masers, we have analyzed the data for VY CMa for which one of the highest signal-to-noise tracks of SMA data exists, amounting to 87 minutes on-source. The radio photosphere of this red, luminous (5×10^5 $L_\odot$ e.g. Humphreys 2006) hypergiant star was found to be unresolved with a $1''$ beam at 22 GHz (Lipscy *et al.* 2005). In the mid-infrared, the same authors measured the size of the warm dust continuum emission to be $0.3''$ at 17.9 μm. In the near-infrared, the K band size was measured to be $0.138'' \times 0.205''$ (Wittkowski *et al.* 1998). SMA observations at 230 GHz continuum with a $1.4''$ beam find the emission to be unresolved (Muller *et al.* 2007). Proceeding with the likely assumption that the 658 GHz continuum emission is likewise compact with respect to the synthesized beam ($1.6'' \times 1.0''$), we generated a continuum dataset using all the correlator chunks in USB except the one containing the maser line. We used that dataset to calibrate the antenna phases and amplitudes with a point source model, and applied the solutions to the spectral line data. A plot of the resulting amplitude vs. uv distance is shown in Fig. 4. There is no discernible drop in

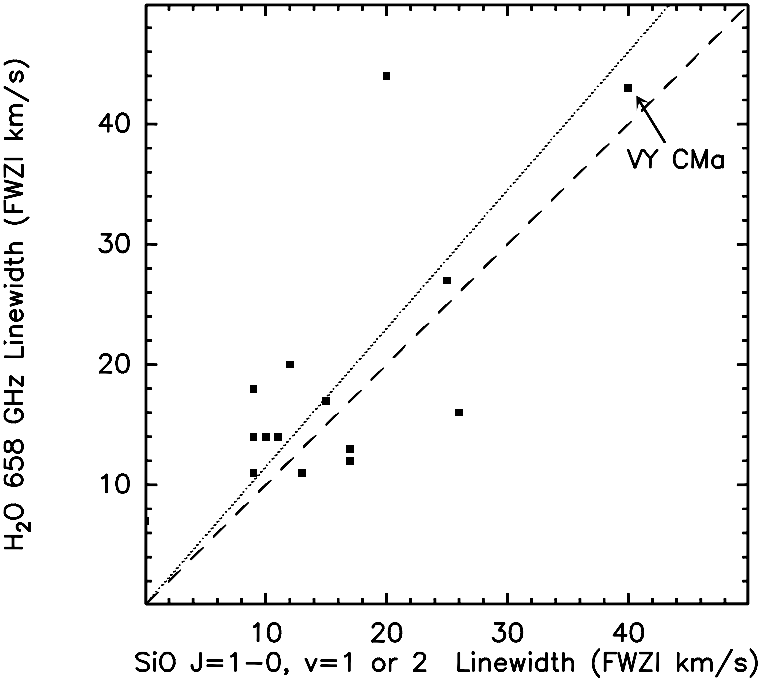

Figure 3. Scatter plot of FWZI of 658 GHz H_2O line vs FWZI of SiO $v = 1$, J=1-0 line (or in some cases J=2-1). The dashed line has a slope of unity, while the best fit dotted line has a slope of 1.15.

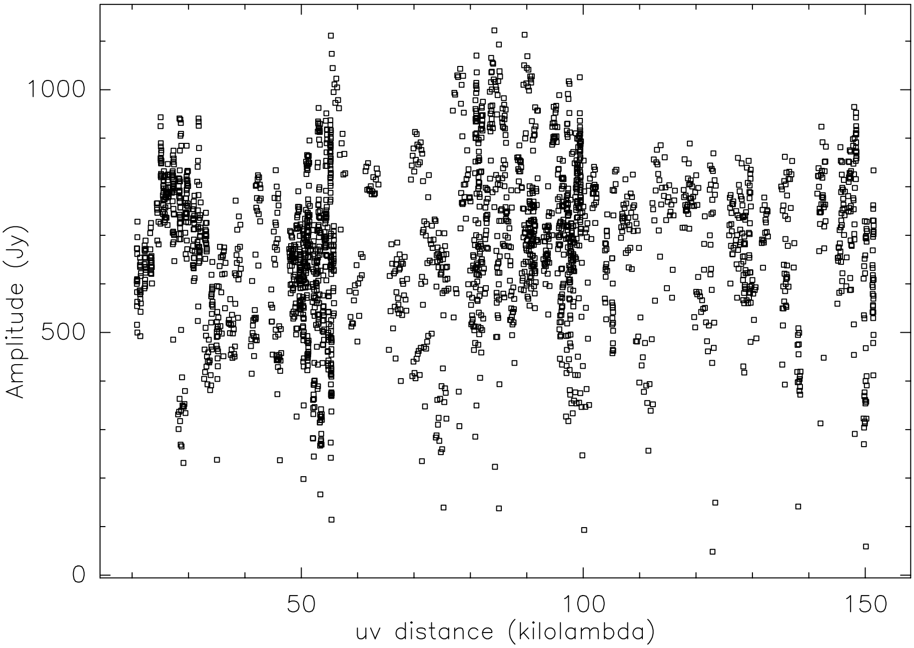

Figure 4. Calibrated amplitude vs. uv distance for the VY CMa 658 GHz maser observations of 16 Feb 2005 with 15 baselines.

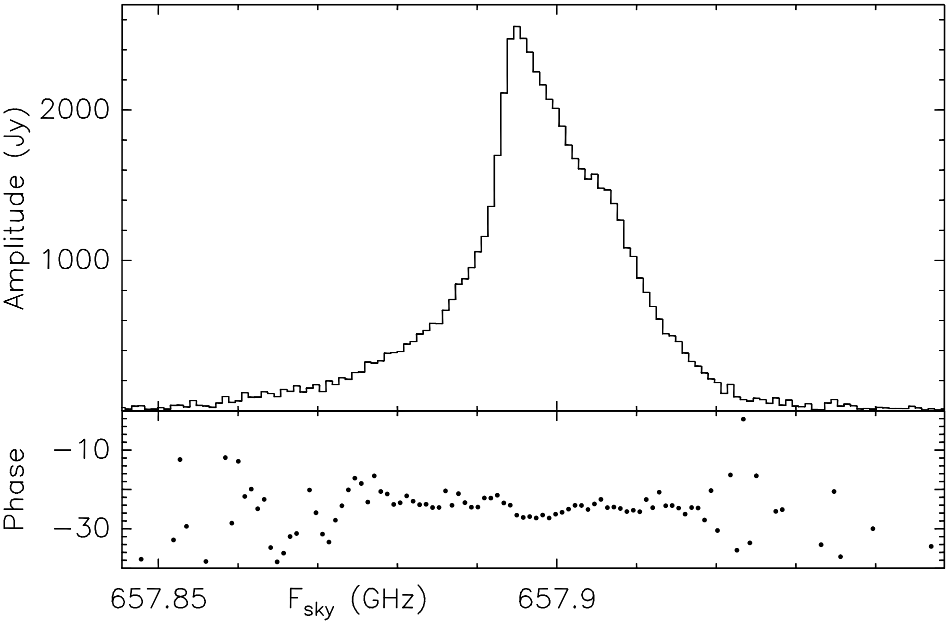

Figure 5. Calibrated phase in degrees (dots) and amplitude (histogram) vs. frequency for the VY CMa 658 GHz maser observations of 16 Feb 2005. This spectrum is a vector average of all 15 baselines.

amplitude with distance, suggesting that the source remains unresolved at these angular scales. Further evidence for this conclusion comes from the uv spectrum (Fig. 5) which shows only a very small phase gradient ($< 10°$) across the spectral line.

4. Phase calibration and phase transfer

Because they are bright celestial beacons, the 658 GHz water masers are helpful in debugging problems in the SMA frontends and backends. The 658 GHz maser line has also served as a successful phase calibrator for SMA observations of other sources. Chen *et al.* (2007) used VY CMa to calibrate observations of the ultracompact HII region G240.31+0.07, located less than 5° away. The measured phase of the water maser emission was used to calibrate the temporal changes in atmospheric phase plus instrumental phase time while the unresolved stellar continuum emission ($\sim$ 9 Jy) was used to calibrate the amplitudes. The 658 GHz maser line has also been used to test the effectiveness of phase transfer between the 200 and 600 GHz bands on the SMA. Using observations of the star W Hydra on 28 Jan 2005, the antenna-based phase solutions for the 215 GHz SiO maser emission and the 658 GHz H_2O maser emission were compared over a period of several hours and shown to change in a ratio close to that expected theoretically (Hunter *et al.* 2005). At SMA, the usage of this technique is limited due to some remaining instrumental thermal drifts and phase jumps currently under investigation (Kubo *et al.* 2006). However, the phase transfer technique is expected to be relied upon heavily by ALMA (Laing 2004), typically from Band 3 (84-116 GHz) where bright quasars are more numerous, to higher frequency bands where they are not (Butler 2003).

5. Future prospects

At the present time, the SMA has the potential to observe the 658 GHz maser sources with a beamsize as small as 0.15″, where it may begin to resolve the emission as a phase

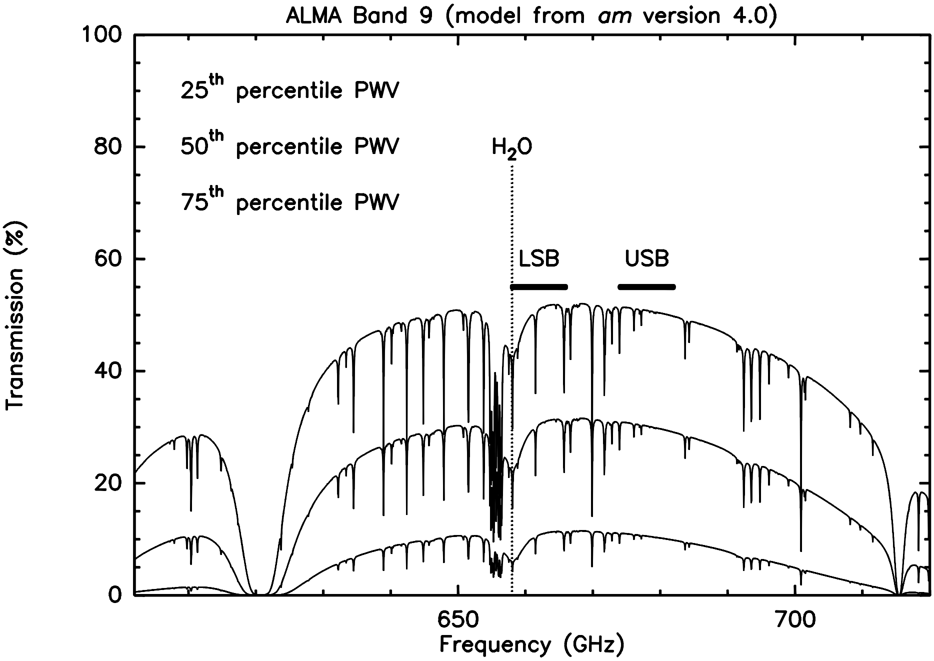

Figure 6. Proposed tuning for 660 GHz continuum observations with ALMA, including the 658 GHz line in the LSB passband in order to use an evolved star as a phase calibrator near the target source. The atmospheric model curves are from the *am* package (Paine 2006). The top curve is 25th %ile conditions, the middle curve is 50th %ile, and the bottom curve is 75th %ile.

gradient in velocity. For example, 43 GHz VLBI observations of TX Cam show a ring of SiO masers with a diameter of $\sim 0.04''$ (Diamond & Kemball 2003). After its launch in 2008, the Band 2 receiver (Teipen *et al.* 2005) of the Heterodyne Instrument for the Far-Infrared (HIFI) aboard the Herschel satellite (Poglitsch *et al.* 2006) will provide the opportunity to perform a sensitive survey of 658 GHz maser emission in a large number of stars. Beginning around 2010, ALMA will become the first telescope capable of observing all five known (sub)millimeter transitions of vibrationally-excited water (Wootten 2007). This capability will be important for obtaining near-simultaneous observations of all these lines in order to accurately determine the temperature and density of the emitting gas. As shown in Fig. 6, the Band 9 receivers of ALMA are DSB and can be tuned to provide the 658 GHz water maser line in the LSB and a 4 GHz region of continuum in the USB that is nearly free of atmospheric ozone absorption features.

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