New facilities

Astrophysical Masers:
Unlocking the Mysteries of the Universe
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Masers and ALMA

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Abstract. Masers have been well-known phenomena for decades, but water masers at 183, 321, 325 and 658 GHz have only been detected since the 1990s. Early detections came from single-dish telescopes with follow-up observations from the PdBI and the Submillimeter Array. Detecting them at these short wavelengths has been very difficult due to water in our atmosphere, meaning that even in very good weather, one can only detect very bright masers, such as those in stellar atmospheres. In the last 7 years, a new window on submillimeter water masers, both Galactic and now extragalactic, has opened. Located at high altitude, above a large fraction of the Earth's atmosphere, ALMA sits on the edge of the driest desert on the planet, meaning that the air that does remain above the telescope is frequently extremely low in water vapor content. Combine this with sensitive, stable receivers covering a number of masing transitions from 183-658 GHz and you have an excellent machine for detecting and characterizing submillimeter water masers. In addition, other molecules also exhibit maser emission in the ALMA observing bands, such as SiO and HCN.

Keywords. instrumentation: interferometers, masers, submillimeter

1. The Attraction and Tribulations of Submm Maser Emission

Early theoretical predictions showed that many maser molecules would have most of their rotational transitions in the submillimeter range (e.g. Neufeld & Melnick 1991, Yates, Field & Gray 1997). More recently, these models were improved by Gray *et al.* (2016) (see his contribution in these proceedings) who performed a thorough exploration of the relevant parameter space (i.e., gas density, kinetic temperature, and dust temperature) for the water molecule specifically and found that many of the submillimeter transitions have emission matching that at 22 GHz. Thus, observing a number of transitions at the same time offers the opportunity to put tight constraints on the physical conditions in the masing regions.

Submillimeter masers hold the promise to constrain and refine the radiative transfer models in regions so far unexplored in cm-wave observations. The amplified emission of several molecules provides a means to probe source temperature and density distributions in a variety of astrophysical sources. Cosmic masers allow us to study a large range of environments, from newly formed stars to the envelopes of evolved stars to nearby or high redshift active galactic nuclei. Maser emission provides unique information, particularly at very high angular resolution owing to its extremely high brightness temperature ($> 10^{10}$ K). Unfortunately, technical and sensitivity limitations, as well as the lack of angular resolution, have rendered observations of these lines extremely difficult until quite recently. Most of the existing maser studies have been carried out in the cm-wave regime where very strong masers like OH, H_2O, and CH_3OH can be studied both by single dish telescopes and with powerful interferometric techniques. However,

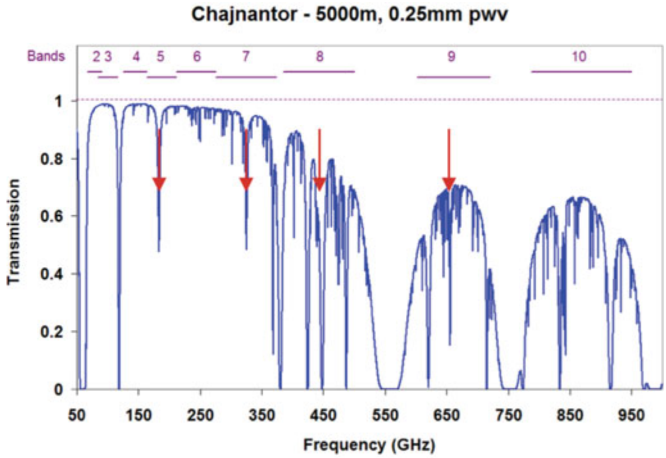

Figure 1. The transmissivity at the ALMA site in reasonably good weather. The purple bars indicate the frequency ranges of the ALMA receivers. The red arrows show the locations of common water maser lines.

until now extending the study of masers to the submillimeter has been challenging in a number of ways. Two big limitations have hindered observations of these transitions. The first one is sensitivity : low sensitivity has been the result of the lack of sensitive receivers that work at higher frequencies and the fact that the radio transmission at those frequencies is severely affected by the atmosphere (Fig. 1). The latter is especially true for the water maser transitions, for example, at 183 GHz and 325 GHz because of their low energies above ground state. The second limitation for the study of sub-millimeter masers has been the lack of high angular resolution observations. Relating cm-wave maser emission observed on milliarcsecond scales with that of the submillimeter maser emission on many tens of arcseconds, has made it difficult to constrain and test the radiative transfer models. The arrival of the SMA, the first submillimeter imaging array capable of sub-arcsecond resolution, and APEX, with more modern and sensitive receivers, have by and large enabled progress in this area in the last decade, especially for the stronger masers.

Now, the Atacama Large Millimeter/submillimeter Array (ALMA), located at an elevation of 5000 m in northern Chile, is in the process of revolutionising the study of astrophysical masers by providing sensitive and stable receivers covering the frequency range from 100-900 GHz, long baselines for high angular resolution and an unparalleled site for observing water and other molecules. Currently carrying out the 5th cycle of science observations, ALMA also offers Band 5 (which includes the promising 183 GHz water maser transition) and baselines of up to ∼16 km. The ALMA archive and science verification observations are readily available and any data that is not proprietary may be downloaded.

2. The Atacama Large Millimeter/submillimeter Array

The Atacama Large Millimeter/submillimeter Array (ALMA) consists of two arrays of high-precision antennas (see Fig. 2). The first one, made up of twelve 7-meter diameter antennas operating in closely-packed configurations of about 50 meters in diameter, is known as the ALMA Compact Array (ACA), also called the Morita Array. The second array is made up of fifty 12-meter antennas arranged in configurations with diameters

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Figure 2. The ALMA telescope. Photo by Pablo Carrillo.

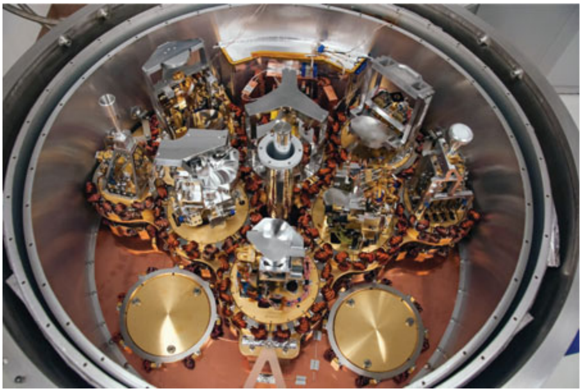

Figure 3. ALMA cryostat showing several receiver inserts. Photo credit: ESO/JAO

ranging from about 150 meter to ∼16 km. Four further 12-meter antennas, for use in conjunction with the ACA, provide "zero-spacing" information, critical for making accurate images of extended objects. The antennas are all equipped with sensitive millimeter-wave receivers covering most of the frequency range 84 to 950 GHz (see Fig. 3). State of the art microwave, digital, photonic and software systems capture the signals, transfer them to the central building and correlate them, while maintaining accurate synchronization.

The ALMA array is situated at 5000 m above sea level, on the Chajnantor plateau in the desert of Atacama, in the northern Chile. The high altitude and dry air are essential for mitigating the phase fluctuations introduced by water vapor and turbulence in the atmosphere. In order to further reduce phase fluctuations in the incoming signals, we use radiometers on each antenna to make measurements of the water vapor content along each line of site through the atmosphere. These radiometers operate at 183 GHz where there is a sufficiently strong emission line of water to give an accurate reading even on short timescales (less than a second) so that the fast fluctuations can be modeled and removed in post-processing.

Antenna integration, commissioning and science verification of ALMA started in 2007, and the telescope was officially inaugurated in September 2013. The first cycle of proposals, Cycle 0 - or Early Science - was offered during the commissioning stage in 2011, with only 16 12-m antennas. Even during Early Science, ALMA represented the most powerful submillimeter interferometer available. Full science operations are now underway, and in August 2017 - just one month before this meeting - the ALMA residencia was opened to host astronomers and engineers working around the clock at the site (see Fig. 4).

Figure 4. The new ALMA residencia. This building houses dormitories, cafeteria and other facilities. Photo by Pablo Carrillo.

ALMA Specifications

- 54 12-m antennas and 12 7-m antennas at 5000m site
- Surface accuracy <25μm, 0.6$''$ reference pointing in 9m/s wind, 2$''$ absolute pointing
- Array configurations between 150m and ~15-18km.
- Angular resolutions ~40mas at 100 GHz (5mas at 900 GHz)
- 10 bands covering 31-950 GHz (not yet all in production) + 183 GHz WVR.
- 8 GHz BW, dual polarization.
- Interferometry, mosaicing & total-power observing.
- 4096 channels/IF (multiple spectral windows, mixed configurations), full Stokes.
- Data rate: 6MB/s average; peak 64 MB/s.
- All data archived (raw + images), pipeline processing.

We are now currently in Cycle 5, with 43 12 m antennas being offered and with bands (3-10) extending continuously from (84-950 GHz), baselines of up to 16 km (yielding up to ~20 mas resolution; see Figure 5), and full polarization products also in Bands 4 and 5. Additionally, as part of a broader collaboration with the Global mm-VLBI Array (GMVA, at Band 3) and Event Horizon Telescope (EHT, at Band 6), ALMA can be used as a single phased array in VLBI mode, achieving resolutions of μarcsecs. The ALMA-VLBI observations will be run for the second time during this cycle (April 2018) but thus far it can only be used for continuum observations. Though still in the commissioning stage, it is foreseeable that spectral line ALMA-VLBI observations will truly revolutionise our maser observations.

3. How Can I Get ALMA Data?

All of the information needed to propose for ALMA can be found at: https://almascience.nrao.edu/proposing/learn-more.

It is important to keep in mind that ALMA has a very high oversubscription rate, and if a proposal is not successful on the first try, it is worth proposing again. At present, masers observations are still perceived as difficult, but we can see from the impressive results that have been published so far that ALMA will be an important tool in maser studies moving forward. The best way to ensure that maser observations become standard is to keep proposing, observing and publishing outstanding results.

In the meantime, it is also possible to download ALMA data directly from the Archive if they were taken in the course of Science Verification, or during an Early Science cycle that

Config	Lmax	Band	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
	Lmin	Freq	100 GHz	150 GHz	183 GHz	230 GHz	345 GHz	460 GHz	650 GHz	870 GHz
7-m Array	45 m	AR	12.5"	8.4"	6.8"	5.4"	3.6"	2.7"	1.9"	1.4"
	9 m	MRS	66.7"	44.5"	36.1"	29.0"	19.3"	14.5"	10.3"	7.7"
C43-1	161 m	AR	3.4"	2.3"	1.8"	1.5"	1.0"	0.74"	0.52"	0.39"
	15 m	MRS	29.0"	19.0"	15.4"	12.4"	8.3"	6.2"	4.4"	3.3"
C43-2	314 m	AR	2.3"	1.5"	1.2"	1.0"	0.67"	0.50"	0.35"	0.26"
	15 m	MRS	22.6"	15.0"	12.2"	9.8"	6.5"	4.9"	3.5"	2.6"
C43-3	500 m	AR	1.4"	0.94"	0.77"	0.62"	0.41"	0.31"	0.22"	0.16"
	15 m	MRS	16.2"	10.8"	8.7"	7.0"	4.7"	3.5"	2.5"	1.9"
C43-4	784 m	AR	0.92"	0.61"	0.50"	0.40"	0.27"	0.20"	0.14"	0.11"
	15 m	MRS	11.2"	7.5"	6.1"	4.9"	3.3"	2.4"	1.7"	1.3"
C43-5	1.4 km	AR	0.54"	0.36"	0.30"	0.24"	0.16"	0.12"	0.084"	0.063"
	15 m	MRS	6.7"	4.5"	3.6"	2.9"	1.9"	1.5"	1.0"	0.77"
C43-6	2.5 km	AR	0.31"	0.20"	N/A	0.13"	0.089"	0.067"	0.047"	0.035"
	15 m	MRS	4.1"	2.7"		1.8"	1.2"	0.89"	0.63"	0.47"
C43-7	3.6 km	AR	0.21"	0.14"	N/A	0.092"	0.061"	0.046"	0.033"	0.024"
	64 m	MRS	2.6"	1.7"		1.1"	0.75"	0.56"	0.40"	0.30"
C43-8	8.5 km	AR	0.096"	0.064"	N/A	0.042"	0.028"	N/A	N/A	N/A
	110 m	MRS	1.4"	0.95"		0.62"	0.41"			
C43-9	13.9 km	AR	0.057"	0.038"	N/A	0.025"	N/A	N/A	N/A	N/A
	368 m	MRS	0.81"	0.54"		0.35"				
C43-10	16.2 km	AR	0.042"	0.028"	N/A	0.018"	N/A	N/A	N/A	N/A
	244 m	MRS	0.50"	0.33"		0.22"				

Figure 5. Receivers and associated configurations available in 2017. For more information, see http://www.almaobservatory.org/en/audience/science/

has passed its proprietary period. The ALMA Archive is searchable by science target or several other parameters, and the interface is located at: http://almascience.nrao.edu/aq/

3.1. *ALMA Science Verification using Masers*

During the commissioning stage of ALMA, a number of science verification observations were taken to test newly integrated components by verifying previously published science results. These observations were usually carried out as a new receiver was installed or a brand new mode was offered to the community. The list of all science verification data acquired to date can be found at: https://almascience.nrao.edu/alma-data/science-verification.

We would like to highlight here two of the science verification results that easily show the ALMA potential to study submillimeter masers.

The first were observations in Bands 7 and 9 of the water masers in VY Canis Majoris (VY CMa; Richards *et al.* 2014). VY CMa was observed on August 2013 using 16-20 12 m antennas on baselines from 0.014-2.7 km. Three water maser transitions were

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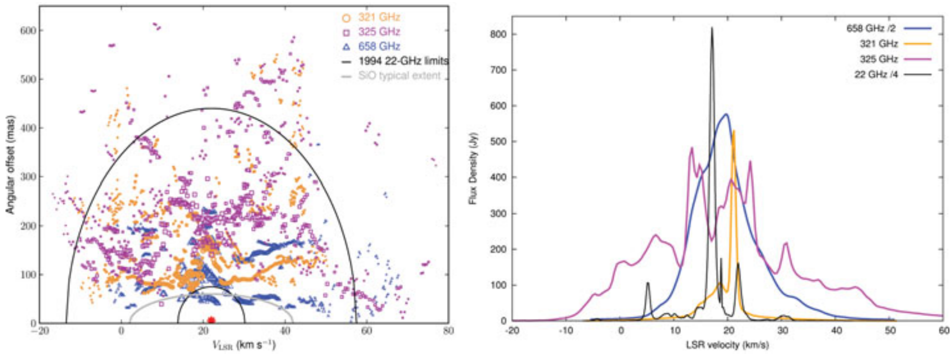

Figure 6. Science Verification results showing the sub-millimeter water masers in VY CMa in Bands 7 and 9. (Richards *et al.* 2014)

observed, namely the 321, 325, and 658 GHz transitions. The velocity resolution after Hanning smoothing was 0.45 km s^{-1} at 321 and 658 GHz, and 0.9 km s^{-1} at 325 GHz. All three sets of maser lines were found at increasing distance from the star, with the 658 GHz masers being closest and 325 GHz further away (see Fig. 6). The masers reached unexpectedly large separations from the central source and the different transitions form clumps but did not overlap even when found at similar separations. This was the first map of submillimeter water masers made at such high precision. The 658 GHz masers displayed half the flux density as the 22 GHz ones (see Fig. 6, right), however observations were not taken at the same time.

The second set of science verification observations we would like to mention were taken during the exciting integration of ALMA Band 5 (163-211 GHz) which was commissioned during Cycle 4 and is finally available this year for the first time.

Observations of the H_2O $3_{13} - 2_{20}$ line at 183 GHz rest frequency were made toward Arp 220 on July 2016 (König *et al.* 2017). The array was composed of 12 antennas equipped with Band 5 receivers in a configuration with baselines ranging from 30 m to 480 m. The emission at 183 GHz was detected in both nuclei of Arp 220. The brightest flux was found in Arp 220 West, with Arp 220 East about three times less luminous.

A comparison of spectra of the 183 and 325 GHz water lines observed at different dates shows that the emission was not variable given the velocity resolution and sensitivity of the data. The 22 GHz observations suggest that the lack of emission in the western nucleus at this frequency is most likely not intrinsic to the physics of the water line, but a result of the strong ammonia absorption. The observed line intensity ratios are not compatible with a pure thermal origin of the water emission, hence may be due to maser emission.

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