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ALMA's view of maser emission

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Abstract. ALMA, the Atacama Large Millimeter/submillimeter Array, provides a large collecting area at a location on a high dry site, endowing it with unparalleled potential for sensitive spectral line observations. Its wide frequency coverage, superb receivers and flexible backend will ensure that that potential is met. Although in the Southern Hemisphere, its tropical latitude ensures good coverage of the northern sky. Since the last meeting on astrophysical masers, the ALMA team has substantially enhanced its capability for line observations. Japan's entry into ALMA has provided increased sensitivity with the addition of the 16 antennas of the Atacama Compact Array, equivalent to eight additional 12m telescopes. The first four cartridges for the baseline ALMA receiver packages (to be augmented by three other bands owing to Japanese participation) have been accepted, with performance above the already-challenging specifications. At first light, ALMA will offer nearly complete frequency coverage of the millimeter and submillimeter spectral windows, ensuring coverage of a variety of masering transitions. ALMA's flexibility as a spectrometer has increased with the enhancement of the baseline correlator with tunable filter banks, and with the addition of a separate correlator for the ACA. As an example of the increased flexibility, ALMA is now capable of multi-spectral-region and multi-resolution modes. With the former, one might observe e.g. four separate transitions anywhere within one of four 2 GHz bands with a high resolution bandwidth. With the latter, one might simultaneously observe with low spectral resolution over a wide bandwidth and with high spectral resolution over a narrow bandwidth. Thus, one could simultaneously cover an extremely broad velocity range while providing high spectral resolution of groups of lines within that range. Several science examples will be presented illustrating ALMA's potential for transforming the millimeter and submillimeter study of masers.

1. Introduction

ALMA will observe the cosmic millimeter/submillimeter spectral region. Millimeter and submillimeter photons dominate the spectral energy distribution of the cosmos, and arise in two spectral components. The most luminous component is the 3K Cosmic Microwave Background (CMB). After the CMB, the strongest component is the submm/FIR component, which carries most of the remaining luminous energy in the Universe, and 40% of that in, for instance, the Milky Way Galaxy. ALMA's wavelength coverage, from 1cm to 0.3 mm, covers both components to the extent that the atmosphere of the Earth allows. In addition to dominating the spectrum of the distant Universe, millimeter/submillimeter spectral components dominate and characterize the spectrum of

† The Atacama Large Millimeter/submillimeter Array (ALMA) is an international astronomy facility. ALMA is a partnership between Europe, North America and Japan, in cooperation with the Republic of Chile. ALMA is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC), and in Europe by the European Southern Observatory (ESO). ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), on behalf of Europe by ESO, and on behalf of Japan by the National Astronomical Observatory of Japan.

planets, young stars, and many distant galaxies. Cool objects tend to be extended, hence ALMA's mandate to image with high sensitivity, recovering all of an objects emitted flux at the frequency of interest. Cool objects present an environment conducive to the existence of molecules. Most of the observed transitions of the 142 known interstellar molecules lie in the mm/submm spectral region – for example some 17,000 lines are seen in a small portion of the spectrum at 2mm. Unfortunately, molecules, particularly water, in the Earth′s atmosphere inhibit our study of many of these molecules. Furthermore, the long wavelength requires large aperture for high resolution, un-achievable from space. To explore the submillimeter spectrum, a telescope should be placed at the highest driest site on Earth. The 5000m Chajnantor site selected for ALMA allows complete spectral coverage using ten frequency bands coincident with atmospheric windows, eight of which will be populated upon the completion of construction.

2. ALMA science

The highest level document governing the ALMA Project is the Bilateral Agreement. Annex B of this agreement details ALMA's three highest level science goals.

•The ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.

•The ability to image the gas kinematics in a solar-mass protostellar / protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.

•The ability to provide precise images at an angular resolution of 0.1". Here the term precise image means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees. These requirements drive the technical specifications of ALMA.

While none of these goals specifically address maser science, they have guided the design of an instrument which directly addresses many issues facing maser astrophysicists. Some maser features which we may enumerate are their small size, their origin in multiple transitions of several molecules with emission across the millimeter/submillimeter spectrum, their association in some cases with weak thermal emission, their appearance in multiple velocity components, often widely separated in velocity, and, for stellar masers, their association with older stars found near the galactic center.

Several features of the ALMA design enable it to address key maser science. Several of these features represent enhancements to the design since the last maser conference, some enabled by Japan joining the project in 2004 September.

•ALMA provides complete frequency access from 31.3 GHz to 950 GHz, with coverage from 84 GHz to 950 GHz available upon completion. Since the previous maser conference, four bands have been added to the first light retinue: 2mm (125 – 169 GHz; provided by NAOJ), 0.6mm (385 – 500 GHz, provided by NAOJ), 1.5mm (163 – 211 GHz, six single polarization receivers, provided by the EU), and 0.35mm (a partial complement of receivers at 787 – 950 GHz, provided by NAOJ with the intention of completely populating the array eventually).

•ALMA has been enhanced by additional antennas, providing the equivalent of 8 12m antennas in collecting area, but comprised of 4 12m antennas and 12 7m antennas deployed in the Atacama Compact Array (ACA) for improved brightness temperature sensitivity, provided by NAOJ.

Table 1. ALMA antenna arrays and configurations

Array	**12m**	**Compact (ACA)**
Number of Antennas	$\leqslant 64^a$	16
Total Collecting Area	$\leqslant 7238\mathrm{m}^2$	915^2
Array Configurations	*(dimension of filled area)*	
Compact filled	150 m	35 m
Largest Extent	18.5 km	
Total No of antenna stations	170	22
Antennas[b]		
Diameter	12 m	4 ×12-m + 12 × 7-m
Surface accuracy	25 μm	12-m:25μm 7-m:20μm

[a] Contracts are signed for provision of at least fifty, up to 64 antennas; two prototypes have already been procured and tested [b] Transportable by specially constructed vehicles with rubber tires

•A more versatile baseline correlator, in addition to a versatile new correlator dedicated to the ACA. Tunable filter bank elements developed by the University of Bordeaux in collaboration with ESO, have brought improved flexibility to the baseline correlator. The ACA correlator has been developed by NAOJ.

•ALMA is located just north of the Tropic of Capricorn, in the southern hemisphere but with good access to objects in the northern hemisphere; the galactic center transits nearly overhead.

•ALMA antennas may be deployed over baselines as long as 16 km on its extensive but high site, enabling it to achieve beamsizes as small as 5 milliarcseconds at its highest operating frequency, similar to the resolution achieved by very long baseline arrays at lower frequencies (Table 1).

•ALMA provides excellent brightness temperature sensitivity (Table 2). A line which is amplified only slightly can easily be identified and measured.

3. ALMA correlators

Of the two baseline correlators, the NRAO Baseline Correlator will be used with the longest baselines and most likely be most relevant to maser observations. There are four quadrants for 64 antennas processing 16 GHz of data for each antenna. The basic sampling is 2 bits but there are limited 3 or 4 bit sampling modes available. The first quadrant of this correlator has been operating for some time in the NRAO Technology Center, to be retrofitted with the Tunable Filter Bank enhancement and installed at the Array Operations Site (AOS) at 5000m in the Technical Building being completed within the next year. A detailed list of observational modes may be found in ALMA Memo No. 556. In addition, the ACA correlator, processing data from 16 antennas, will be installed in the building at about the same time.

Both correlators are very flexible. An observer may specify a set of disjoint or overlapping spectral regions for observation, each characterized by bandwidth ranging from 31.25 MHz to 2 GHz. Each of the eight available 2 GHz baseband inputs drives 32 tunable digital filters, which may be placed as desired within the baseband. A number of products are available: autocorrelation or correlation, several polarization products (XX or YY; XX and YY; XX, YY, XY and YX), and improved sensitivity (4x4 bit correlation or double Nyquist modes). The temporal resolution depends upon the mode and varies from 1 msec for autocorrelation and from 16 to 512 msec for cross correlation. The correlators offer simultaneous pseudo-continuum and spectral line operation.

Table 2. 'First Light' front ends on all antennas[a]

Band	λ mm	ν GHz	Type	Continuum Sensitivity (mJy)[b]
Band 3	3	84-116	SIS	0.04
Band 4	2	125-169	SIS	0.06
Band 5	1.5	163-211	SIS	[b]
Band 6	1.3	211-275	SIS	0.11
Band 7	0.9	275-373	SIS	0.19
Band 8	0.6	385-500	SIS	0.70
Band 9	0.5	602-720	SIS	1.0
Water Vapor Radiometer	1.6	183	Schottky	...

[a] Baseline ALMA plan; all are planned to have dual polarization with noise performance limited by atmosphere. [b] See the ALMA sensitivity calculator at http://www.eso.org/projects/alma/science/bin/sensitivity.html; these numbers are for nominal atmospheric conditions and one minute of integration at band center.

Table 3. Brightness temperature sensitivity of ALMA, 14.7 km baseline

Band	λ mm	Beam	ΔT (Line Sensitivity) (1 km s^{-1}, K)[a]
Band 3	3	0.038	482
Band 4	2	0.030	495
Band 5	1.5	0.022	9500[b]
Band 6	1.3	0.018	709
Band 7	0.9	0.012	1128
Band 8	0.6	0.010	1569
Band 9	0.5	0.006	4305

[a] See the ALMA sensitivity calculator at http://www.eso.org/projects/alma/science/bin/sensitivity.html; these numbers are for nominal atmospheric conditions and one minute of integration at band center. [b] Only a partial receiver complement is available at first light, single polarization.

The observer might set up multiple spectral windows within any of the 2 GHz basebands for modes with total bandwidth from 125 MHz to 1 GHz. This will prove useful for high spectral resolution observations, which can be provided over a large bandwidth for sources such as masers and which can show complex narrow emission over a vast velocity range. One may also have multi-resolution modes, which may prove useful for sources with different characteristic linewidths such as planetary atmospheres or star-forming cores containing outflows, rotating disks and quiescent material. As one ALMA goal is ease of use, the ALMA Observing Tool will guide the observer through the maze of possibilities.

4. Example

There are many molecules known with transitions having maser action within the ALMA bands. A summary is given in Table 3. Of particular interest is the abundant and simple water molecule, which emits in all of the ALMA bands. Owing to its abundance, water is an excellent tracer of star-forming regions, where it is seen in shocks and warm, chemically active regions. ALMA's high resolution, excellent brightness temperature

Table 4. ALMA bands with known masering lines

Array	**12m** and **Compact (ACA)**
Species	Bands
H_2O	B3, B5, B6, B7, B8, B9
CH_3OH	B1, B3, B4, B6
SiO	B1, B2, B3, B4, B5, B6, B7
HCN	B3, B5, B6, B7, B9
Etc: H$n\alpha$, SiS	B3, B4, B6, B7, B9

sensitivity, spectral coverage, polarization capability and flexibility will prove particularly useful in these regions. These features will also serve science projects which target objects as diverse as evolved stars and galactic nuclei.

Water is perhaps the most observed of these as it incorporates two of the three most abundant elements in the Universe, has a myriad of transitions and has a singular importance in cooling interstellar clouds. Owing to its very high brightness temperatures and ubiquity, it has been used as a probe of interstellar shocks, including measuring their motion across the sky, and for measuring parallactic distance, normally through Very Long Baseline (VLB) techniques using its 22 GHz line. Owing to its exceptionally dry location high on the Chilean Altiplano, ALMA can observe many additional lines from both higher and lower energy levels. Some of these transitions occur at sufficiently high frequency that ALMA can achieve near-VLB resolution across its 15 km baselines. Since the ALMA brightness temperature sensitivity is so high, one can literally watch chemistry taking place behind the shocks. Water masers are also sent coursing through the atmospheres of evolved stars as they pulsate. In both these environments, high magnetic fields can cause observable Zeeman splitting in the lines, leading to magnetic field measurements. ALMA will also be able to constrain conditions in masers spiraling inward toward black holes in galactic nuclei by simultaneously observing several lines at once; the enormous bandwidth of the receivers and correlators will be particularly useful for this task.

The power of the instrument is perhaps best demonstrated by an example. We will illustrate one receiver/correlator setting at 321-337 GHz, which encompasses three lines of water emission at different excitations, two lines of water isotopes as well as a selection of other lines of shock tracers such as methanol, SO, SiO and SO_2. A main target of this setting is the para-H_2O $J_{K_a K_c}$ 5_{15} - 4_{22} line at 325.15 GHz, which lies at an energy 470 K above ground. At such a low energy, this line is strong in the Earth's atmosphere and only very limited observations have been made (see review by Humphreys in this volume (Humphrey 2007) since its discovery by Menten *et al.* (1990). A line from the ^{18}O isotopomer of this same water line lies at 322.97 GHz, in the center of the band. At the lower end of the same 4 GHz lower sideband, just fitting in, lies the higher energy (1861 K) ortho-H_2O $J_{K_a K_c}$ 10_{29} - 9_{36} line at 321.23 GHz. In the upper sideband, 8 GHz higher in frequency, lie two water lines, the HDO $J_{K_a K_c}$ 3_{31} - 4_{22} line at 335.40 GHz, 319 K above ground, and the ortho-H_2O $J_{K_a K_c}$ 5_{23} - 6_{16} $\nu_2 = 1$ line at 336.23 GHz, 2939 K above ground. Sprinkled throughout the band are the additional lines of SO, SO_2 and CH_3OH. For the largest configuration, the ALMA beam will be 14 milliarcsec. In 8 hours of integration, during best octile weather (0.52 mm of precipitable water vapor) the resulting spectrum should have an rms in the center of the atmospheric line of $\Delta T = 52$ K, or about 0.8 mJy. For 5s integrations, the 30Mbytes/s data rate exceeds the average ALMA rate of 6 Mbyte/s but fits comfortably within the allowed maximum, producing a dataset of 860 MB size.

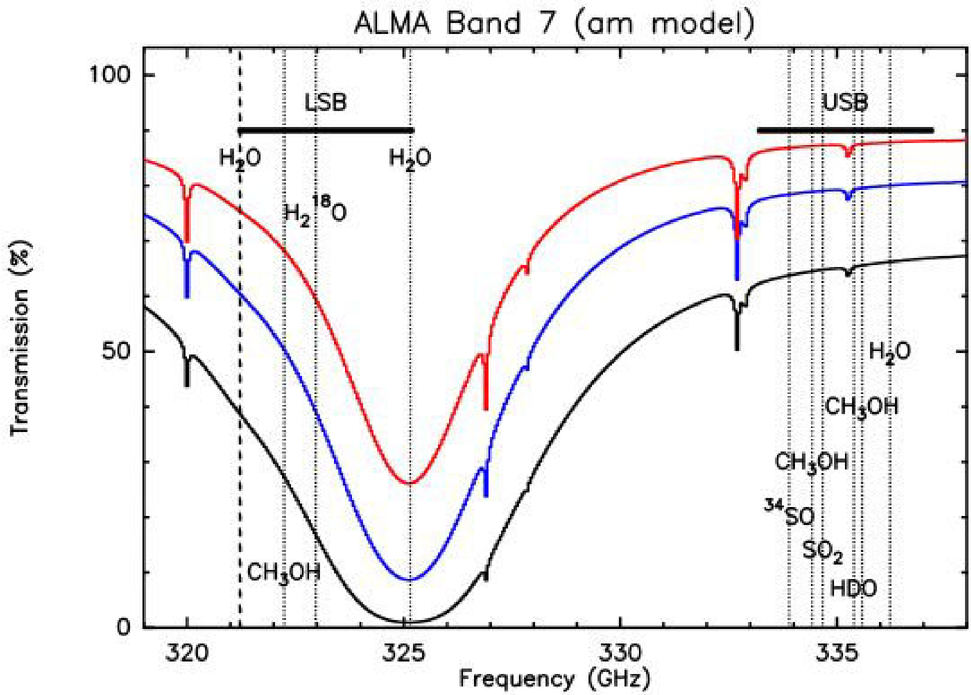

Figure 1. Atmospheric transparency for the ALMA site during the 25% weather quartiles is plotted against the receiver sideband setup with the targeted spectral lines.

Water is also of interest in stars, though the other molecules in the setup are of only occasional interest. However, some isotopic and highly excited vibrational states of SiO lie within the band.

5. Conclusions

ALMA's complete frequency access across atmospherically accessible bands, its large collecting area and excellent brightness temperature sensitivity, its high altitude equatorial location, and its high resolution make ALMA an ideal instrument for study of the astrophysics of masers.

References

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