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GALAXIES AND COSMOLOGY WITH ALMA

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Abstract. Intensive work is being carried out at the Joint ALMA Observatory in order to bring four bands of a 16-antenna mm/submm interferometer into scientific operation. Specific tests of the advertised capabilities for Early Science are being carried out as well as further tests in order to bring ALMA into full operation as planned. Some of the measurements were taken towards extragalactic objects. In fact, the high sensitivity, high angular resolution, high image fidelity, and high mapping speed, together with a large frequency coverage, will make ALMA the right instrument for high redshift studies, and detailed dynamical and chemical studies of nearby galaxies.

Keywords: galaxies, high-redshift, cosmology, observatories, ALMA

1 Introduction

The Atacama Large Millimeter/submillimeter Array (ALMA), the larger astronomical project in existence (cf. `http://www.almaobservatory.org`), is planning to start the Early Science readiness Cycle 0 on fall 2011 (cf. `http://www.almascience.org`). The capabilities of the instrument will be limited (to four frequency bands and to 16 antennas, giving about one third of the full collecting area of the final 50 antenna main array) and observations will be conducted on a best effort basis. Nevertheless, almost one thousand proposals were submitted by the end on June by astronomers of all over the world, showing the large interest of the community in using this instrument, specially for extragalactic and cosmology research. In fact, if the 2009 ALMA Design Reference Science Plan (hereafter DRSP, `http://www.eso.org/sci/facilities/alma/science/drsp/`) and the 600 notices of intent received by end of April 2011 were good indicators, extragalactic and cosmology will account for about half the number of proposals*, a share that could well be maintained when ALMA delivers its full performance in a couple of years.

2 The Joint ALMA Observatory science teams

The construction and commissioning of an observatory is not only a task of constructors and technical staff, but of astronomers as well. The effort of assembling and characterizing the individual radiotelescopes started by the beginning of 2008, carried out by the Assembly, Integration and Verification (AIV) team, that included a handful of astronomers. A larger team is currently carrying out the Commissioning and Science Verification (CSV) tasks in order to have the interferometer ready for Early Science and also testing additional capabilities planned for the final instrument. The Science Operations team, involved in both the AIV and CSV tasks, is getting the knowledge to perform all sorts of observations and analysis to deliver the data to the final users, via the ALMA Regional Centers (ARCs). Astronomers in the ARCs actively collaborate in the CSV tasks either remotely or by spending short periods in Chile. The current JAO staff in Chile includes around 35 astronomers.

By the time of the Paris meeting, the AIV team had already fully checked (control, tracking, pointing, switching, on-the-fly mapping, tuning, spectral checks, interferometry) and optimized (surface, focus) 15 antennas to within science specifications. They had subsequently been delivered to the ALMA Operations Site (AOS) at 5000 m above sea level and integrated in the interferometer being tested by the CSV team. Tests at baselines up to 600 m long were carried out successfully. Measurements of continuum and line sensitivity,

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*It turned out to be: Cosmology and the high redshift universe 20%; Galaxies and galactic nuclei 27%.

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Table 1. Band 3 at 115 GHz: FOW, angular and linear resolution

	Field of view	**z=0.0036 (Virgo cluster)**	**z=2**
12 m antenna	54″	4.0 kpc	458 kpc
	Angular resolution	**z=0.0036 (Virgo cluster)**	**z=2**
Early Science compact (125 m)	4.30″	320 pc	36 kpc
Early Science extended (400 m)	1.34″	100 pc	11 kpc
Full operations most extended (16 km)	34 mas	2.5 pc	285 pc

For band 6 at 230 GHz (CO 2–1 rest frequency): divide by 2
For band 7 at 345 GHz (CO 3–2 rest frequency): divide by 3
For band 9 at 692 GHz (CO 6–5 rest frequency): divide by 6

frequency resolution, imaging fidelity and dynamic range, and amplitude calibration, bandpass calibration and positional accuracy were done.

Several end-to-end projects were selected out of a suggestion list made by the ALMA science teams and the community, including nearby as well as high-redshift galaxies. When possible, the observations were compared for consistency with the results obtained with other instruments, either interferometers (IRAM Plateau de Bure, SMA) or single dish telescopes (IRAM Pico de Veleta, APEX). Continuum-like and low frequency resolution CO measurements in all bands were done towards NGC 253. HCN and HCO^+ absorption lines discovered by Wiklind & Combes (1998) at $z = 0.8858$ towards the $z = 2.5$ gravitationally lensed quasar PKS 1830-211 were measured too. And the 158 micron [CII] line redshifted at $z = 4.43$ towards the gravitationally lensed quasar host BRI 0952-0115 discovered by Maiolino et al. (2009) was also measured, in band 7. All these observations were done with a handful of antennas so providing only a glimpse of what ALMA Early Science can produce.

Some datasets have been made publicly available (cf. `http://almascience.eso.org/alma-data/`). They are provided as a means for the user to become acquainted with the ALMA data structure, observing strategies and reduction techniques. In fact, the early band 3 observations of the luminous galaxy NGC 3256 (a merger of two gas-rich galaxies, now in its later stages) come with a detailed data reduction tutorial (`http://casaguides.nrao.edu/index.php?title=NGC3256Band3`).

3 The Early Science instrument

Sixteen 12-m antennas in a single array will provide 120 baselines, that allow for a rather fast mapping speed. Two configurations will be available, a compact one with baselines up to 125 m and an extended one providing a 3 times better angular resolution (cf. Table 1). Observations will consist of single fields or small mosaics of up to 50 pointings.

All the antennas are equipped with at least four observing bands, covering partially the frequencies between 84 and 720 GHz (or wavelengths between 417 micron and 3.6 mm). This ensures that at all redshifts (except for tiny gaps) at least two CO transitions can be observed (Fig. 1, left panel). In the future, all antennas will be equipped with band 4, 8 and 10 receivers, consequently at least three CO transitions will be available at any redshift lower than 7.3 (Fig. 1, right panel), allowing for excitation studies or line SED determinations. In Early Science up to 4 basebands (or spectral windows) of bandwidth 0.06 to 2 GHz and resolution 0.015 to 1 MHz will be available simultaneously, providing a spectral resolution in the range $R = 10^{4.9} - 10^{7.7}$ and a velocity resolution down to 0.006 km s^{-1}.

Some intense fine structure atomic lines (e.g. [CII] at 157.74 μm, [OIII] at 88.35 μm and [OI] at 63.18 μm) can also be observed with ALMA in some frequency ranges, provided that the redshift is large enough (Fig. 2), e.g. the [CII] line can be observed in band 9 for $1.64 < z < 2.16$ or in bands 6 and 7 for $4.1 < z < 8.0$. This line, the main coolant of the interstellar medium (ISM), may be better than CO lines to study the extreme redshifts, i.e. the Epoch of Cosmic Reionization at $z > 6$ (bands 6, 4 and 3).

At full operations the ALMA main array will consist of 50 12-m antennas, providing more than a thousand simultaneous baselines. The maximum baseline will be extended to 16 km, providing milliarcsecond resolution. An additional 16 antenna compact array (ACA) with baselines up to 50 m will be available. Bands 4 and 8 will be added first, plus band 10 and possibly band 5 in a few antennas. A more versatile use of the correlator will provide up to 32 spectral windows within a 8 GHz passband. True continuum, full polarization and solar observations will be available, as well as increased mosaicing possibilities.

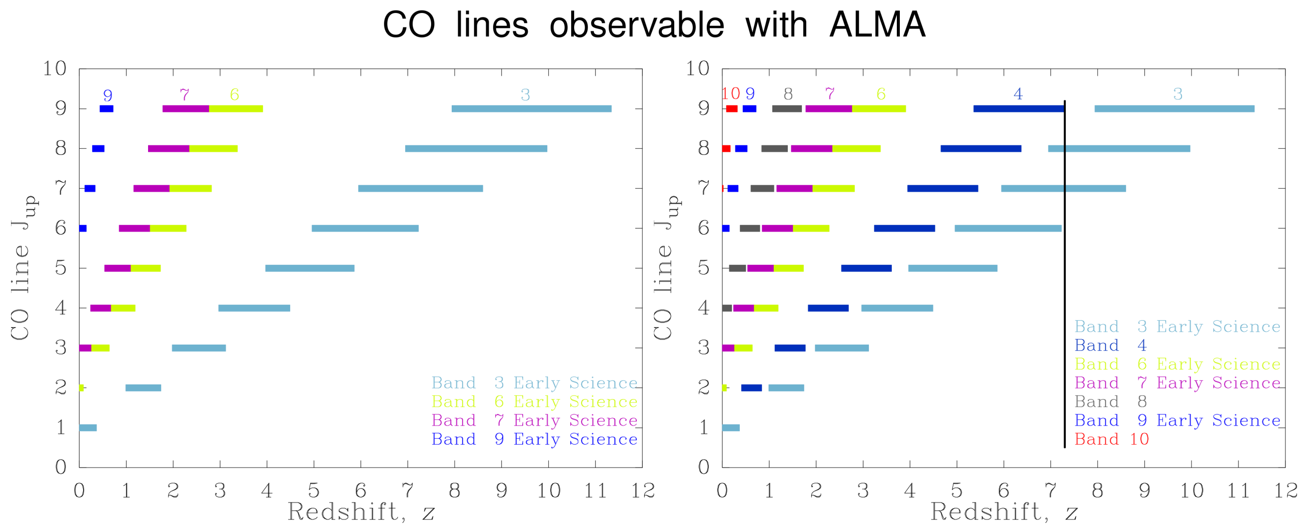

Fig. 1. CO lines observable with ALMA receivers as a function of redshift up to $z = 12$. **Left:** receivers available in Early Science. **Right:** with all receivers currently being build. The vertical line at $z = 7.30$ shows the redshift limit for three different CO lines being observable towards a high redshift object.

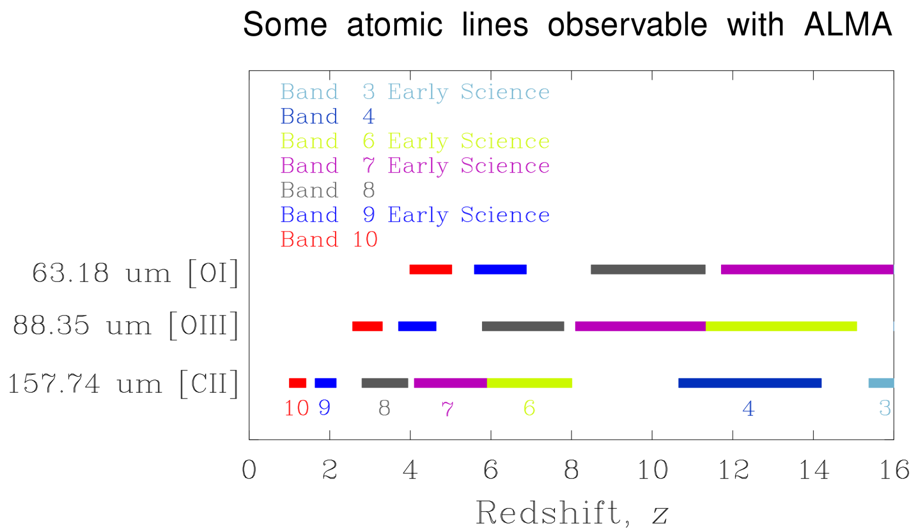

Fig. 2. Redshift ranges (up to $z = 16$) for the observation of some atomic fine structure lines with the ALMA receivers currently installed or being build.

4 Extragalactic science with ALMA at full operations

The high sensitivity (collecting area of 5.600 m^2), high angular resolution (0.21″ λ_{mm}/L_{km}), large frequency coverage (almost full from 84 to 500 GHz, plus the 602-720 GHz and 787-950 GHz windows) and high mapping speed (∼1200 baselines), together with the high quality of the site (< 1 mm of water vapour for most of the operational time, cf. `http://www.apex-telescope.org/sites/chajnantor/atmosphere/pwvvar/`), will make ALMA the right instrument for high redshift studies, and detailed dynamical and chemical studies of nearby galaxies. In particular, the negative K-correction will allow to study the continuum SED of starburst galaxies with nearly equal sensitivity in the redshift range $1 - 10$ for wavelengths longer than 0.8 mm, that is up to band 7. A further consequence is that, in contrast to what is observed in the optical, we expect to see many more objects with high redshifts (say $z > 1.5$) than at lower redshifts.

A little survey of what has been proposed in the past (e.g. the previously quoted DRSP, Maiolino 2008, Bachiller and Cernicharo 2008) can give some insight of scientific goals that will be achievable with ALMA at full operations. Some large scientific projects that could be carried out by continuum observations (using mainly the higher frequency bands) at high redshift follow:

1. Ultradeep surveys of well studied fields (UDF, COSMOS, GOODS-S) to probe the formation and evolution of galaxies, targeting the highest redshifts.

2. Unbiased surveys to detect submillimeter galaxies (SMGs) and determine their size, likely followed by redshift and dynamical mass determinations using bands 3 and 6 spectroscopic measurements. The goal is to study galaxy evolution and the epochs of higher rates of (dust obscured) star formation.

3. Ultradeep surveys through clusters to image magnified background galaxies to determine the properties of the population of faint, young galaxies.

4. Detection (band 6) and multicolor images (bands 3 to 6) of selected sources (from Spitzer, Planck, LBGs or SMGs catalogs) to determine their SED and characterize the star formation rate history.

5. Map the dust emission of gravitational lenses (high bands) to better constrain the shape of their lensing potential.

6. Study merging clusters and the fine structure of clusters via the Sunyaev-Zel'dovich effect (band 3).

The expected detection sensitivity in radio continuum is $5\sigma = 0.11$ mJy/beam in 1 hour in band 7 (0.35 mJy/beam for Early Science) for two 8 GHz bandwidth polarizations and 1 mm of water vapour.

The molecular gas content and properties will be studied at all redshifts in spectroscopic mode. The expected sensitivity varies strongly with the angular resolution, that is with the maximum baseline length ($L_{\rm max}$). In bands 3 to 6, for a velocity resolution of 10 km s^{-1} and the compact configuration ($L_{\rm max} = 150$ m), we expect a brightness temperature line detection sensitivity of $3\sigma \sim 10$ mK in one hour (in 4 hours for the Early Science compact configuration). To estimate the sensitivity for other configurations, consider that the line sensitivity scales as $L^2_{\rm max}$.

One of the three main scientific requirements for the ALMA design was that it must be able to map the CO and [CII] spectral lines in a Milky Way galaxy at a redshift of $z = 3$ in less than 24 hours, so normal galaxies can be studied at moderate redshifts. Galaxies with a richer interstellar medium can be studied at even larger redshifts. Some spectroscopic projects that can be undertaken are:

1. Single line (CO) blind surveys of SMGs to get their redshift distribution.

2. Line studies (CO, HCN, HCO^+, CN, H_2O) of SMGs to search for dense gas and, perhaps, determine a chemical classification.

3. Coolant line ([OI], [CII]) studies of the interstellar medium in high-z ULIRGs and ISM-rich objects.

4. Search for high-z line emitting galaxies and also moderate-z field galaxies, in order to characterize their properties.

5. Detect rare molecules at high redshift via molecular absorption towards QSOs, a procedure that can also be applied to the nearby Magellanic Clouds.

6. Study the shape distortion and gas kinematics in lensing systems.

7. Map the CO distribution in order to determine dynamical masses, e.g. towards moderate and high-z ULIRGs and infrared luminous QSOs.

The high image reconstruction fidelity provided by ALMA, specially when combining the main array and ACA data, will be of great importance in nearby galaxy studies. The high sensitivity will allow the study of large samples. In fact, it has been estimated that all spirals within $1 - 25$ Mpc can be mapped at $1''$ angular resolution and 10 km s^{-1} velocity resolution in less than two months (Sakamoto 2008). Large, massive (5 10^6 $M_\odot$) giant molecular clouds (GMCs) can be detected at a 200 Mpc distance (that of Mrk 231) in one hour with ALMA. Projects involving individual GMCs:

1. Study the distribution, kinematics and chemistry of GMCs and the interstellar medium in a variety of galaxy types and environments.

2. Resolve GMCs to determine virial masses and contribute to the determination of the integrated CO 1 $\rightarrow$ 0 line emission to H_2 column density conversion factor $\chi_{1\,0}$ in galaxies with different metallicity.
3. Extend the GMC studies to higher CO J+1 $\rightarrow$ J transitions in order to study the line excitation conditions and establish the conversion factors $\chi_{J+1\,J}$ required for high-z studies.

Studies of the nuclei of nearby galaxies suitable for ALMA:

1. Resolve the nuclear molecular torus of nearby AGNs down to a few parsecs.
2. Study outflow and feedback processes in the vicinity of AGNs and at larger scales, as they could play a key role in galaxy evolution.
3. Study the star formation efficiency in normal, starburst and infrared luminous galaxies and, specifically, determine the role of the dense molecular gas.
4. Resolve circumnuclear starburst rings down to individual GMC complexes, and study the gas distribution and kinematics in relation to star formation processes and to gas flows, e.g. those induced by bars.
5. Study the dense gas content and its physical conditions via multitransition observations, and probe the environment via multiline studies that allow to discriminate between shocks, PDRs and XDRs.
6. Studies of the chemical complexity of the interstellar medium in a variety of galaxy types, using several lines in a number of molecules, high angular resolution to identify their location and extend, and high sensitivity to detect the less abundant ones.
7. Study the kinematics and dynamics of the ISM at small to large scale in nearby isolated and interacting galaxies.

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