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The exciting future of (sub-)millimeter interferometry: ALMA

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Abstract. The Atacama Large Millimeter/submillimeter Array (ALMA), presently under construction, is a revolutionary astronomical interferometer, that will operate at (sub)millimeter wavelengths. With unprecedented sensitivity, resolution, and imaging capability, ALMA will explore the (sub-)mm Universe, one of astronomy's last frontiers. ALMA is expected to provide insight in star- and galaxy formation in the early Universe and to image local star- and planet formation in great detail. The ALMA Commissioning and Science Verification phase is currently in course, preparing the path for Early Science. The Call for ALMA Early Science proposals is expected to be released before the end of 2010. In this contribution we will describe the ALMA project, the array and its receivers, its science goals, and its scientific and technological potential. We will outline the organizational structure of the ALMA Regional Centres, that will play an important role in providing support to the users, with particular attention to the Italian ALMA Regional Centre in Bologna. Finally, we will illustrate what ALMA can contribute to the specific science case of AGN fueling.

Key words. Instrumentation: interferometers – Instrumentation: high angular resolution – Galaxies: individual: NGC 5953 – Galaxies: active – Galaxies: nuclei

1. Introduction

In essence, the Atacama Large Millimeter/submillimeter Array (ALMA) is a radio interferometer, that because of its design *and* its unique location will allow us to perform ground-breaking science in the field of millimeter (mm) and submillimeter (sub-mm) astronomy.

ALMA, thanks to its unprecedented sensitivity and resolution, will open up a new window onto the cold Universe, capturing never-before seen details about the very first stars and galaxies in the Universe, and directly imaging the formation of planets.

In Sect. 2, we briefly describe the global collaboration behind ALMA and the present status of the project. The main technical specifications and the primary science goals of ALMA are presented in Sects. 3 and 4, respectively. Early Science observations are described in Sect. 5. In Sect. 6 we outline the organizational stucture of the ALMA Regional Centres, and their role in providing support to future users with proposal preparation and post-observation data reduction. Particular attention will be given to the Italian node of the

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Send offprint requests to: V. Casasola network. Finally, Sect. 7 shows a specific example of a science project, and how this will benefit from observations with ALMA.

2. ALMA: A global collaboration

ALMA is designed to explore the cold Universe by means of observations of mm and sub-mm radiation, at wavelengths between 0.3 and 3 mm. Since in the (sub-)mm range the signal from space is heavily absorbed by water vapour in the Earth's atmosphere, instruments operating at these wavelengths must be built on high and dry sites. For ALMA, the 5000 m high plateau at Chajnantor has been chosen, one of the highest astronomical observatory sites on Earth. The ALMA site, ~50 km east of San Pedro de Atacama in northern Chile, is also one of the driest places on Earth.

ALMA is a truly global endeavour, a partnership between Europe, North America (USA and Canada), and East Asia (Japan and Taiwan), in cooperation with the Republic of Chile. The project development is coordinated by the Joint ALMA Office (JAO), based in Santiago de Chile.

The ALMA Observatory will operate at two distinct sites: the Operations Support Facility (OSF) and the Array Operations Site (AOS). The AOS lies at an altitude of 5000 m and is where the array and correlator will be located when ALMA is in operation. The OSF is situated at ~2900 m altitude and will be the base camp for the routine operations of the observatory. The OSF is the focal point of all antenna Assembly-Integration-Verification (AIV) activities. During the AIV-stage the antennas are assembled, integrated with the other subsystems (electronics, receivers), and tests are performed to ensure that the system satisfies the astronomical requirements. The antennas are then transported to the AOS, 28 km away and 2100 m higher. With the delivery of 3 fully equipped and functioning antennas to the high site in January 2010, the Commissioning and Science Verification (CSV) stage began. In short, the goal of the CSV is to test the operation of the ever-growing array and to obtain quantitative confirmation that the data have the required characteristics in terms of sensitivity and image quality.

The day-by-day operation of the observatory and all maintenance will take place at the OSF. During the operations phase of the observatory, the OSF will be the workplace of the astronomers and of the teams responsible for maintaining the proper functioning of all the telescopes. The quality of all ALMA data will be assessed at the OSF. In other words, the OSF will be, in many aspects, the centre of activities of the ALMA project, while human operations at the AOS will be limited to an absolute minimum, due to the high altitude.

The development of ALMA is proceeding rapidly: preparation of the site started in late 2005, and construction will be completed in 2013. The first prototype antenna was tested (at the VLA in Socorro) in 2003; first fringes between two antennas were detected there in March 2007, and a month later the first ALMA production antenna arrived in Chile. In mid-2009 two-antenna interferometry was done at the OSF, and by the end of that year 3-antenna interferometry and phase closure was achieved at the AOS. Commissioning and Science Verification started in early 2010. Presently there are 8 antennas at the high site.

3. ALMA technical specifications

The ALMA interferometer operates at wavelengths between 0.3 and 3.0 mm (84 to 720 GHz). It will be composed initially of 66 antennas, with a possible extension in the future. The main array is constituted of fifty 12-m diameter antennas, In addition, twelve 7-m diameter antennas for interferometry and four 12-m diameter antennas for total power observations form the Atacama Compact Array (ACA). The ACA is used to obtain short spacing data. Because two antennas can not be placed closer than some minimum distance ($D_{\rm min}$ = 15 m for the ALMA array), signals on spatial scales larger than some size ($\propto\lambda/D_{\rm min}$) will not be detected. This effect, called the "missing flux" problem, is resolved by observations with the ACA and by then combining the ACA-data with the main array measurements. Therefore, the ACA works together

Table 1. Main parameters of ALMA receiver bands.

Band	Frequency range [GHz]	Wavelength range [mm]	Angular resolution $b_{\max} = 200\,\mathrm{m}$–$16\,\mathrm{km}$ [″]	Line sensitivity [mJy]	Continuum sensitivity [mJy]	Primary beam [″]	Largest scale [″]
3	84–116	2.6–3.6	3.0–0.034	8.9	0.060	56	37
4	125–169	1.8–2.4	2.1–0.023	9.1	0.070	48	32
5	163–211	1.4–1.8	1.6–0.018	150	1.3	35	23
6	211–275	1.1–1.4	1.3–0.014	13	0.14	27	18
7	275–373	0.8–1.1	1.0–0.011	21	0.25	18	12
8	385–500	0.6–0.8	0.7–0.008	63	0.86	12	9
9	602–720	0.4–0.5	0.5–0.005	80	1.3	9	6

with the main array in order to enhance the wide field imaging capability.

The main array can be configured in various ways, ranging in size between 200 m and 16 km, in order to achieve specific imaging requirements. Compact configurations are indicated to image extended sources because they are more sensitive to low surface brightness features, while extended configurations allow one to achieve a better resolution (at the expense of surface brightness sensitivity). ACA on the other hand, will have essentially one configuration (~50 m in size) with the possibility of a slight north-south extension to reduce blockage of the inner antennas by the other ones when observing sources at northern declinations.

Table 1 collects the main parameters of ALMA receiver bands. In this table, Col. (1) indicates the number of the ALMA receiver band; Cols. (2) and (3) the frequency and wavelength ranges, respectively, covered by each band; Col. (4) the angular resolution for the most compact and the most extended configurations; Cols. (5) and (6) the line and continuum sensitivities, respectively; Col. (7) the primary beam size; and Col. (8) the largest observable scale in a given band.

The frequency range available to ALMA is divided into 10 receiver bands, that can be used only one band at a time. ALMA will operate initially in 7 bands: from band 3 to 9 (see Table 1 for a list of the main parameters). Bands 1, 2, and 10 at ~40 GHz (7.5 mm), ~80 GHz (3.7 mm), and ~920 GHz (0.3 mm), respectively, might be added in the future.

The spatial resolution depends on the observing frequency and the maximum baseline of the array. In the most compact ALMA configurations (200 m), the spatial resolution ranges from $0\farcs4$ at 675 GHz to $2\farcs8$ at 110 GHz, while in the most extended configuration, it ranges from 6 mas at 675 GHz to 38 mas at 110 GHz. The receivers have an instantaneous bandwith of 8 GHz, that can be divided in up to 4 spectral windows of up to 2 GHz each. ALMA can produce data cubes with up to 8192 frequency channels, whose width may range between 3.8 kHz and 2 GHz.

The field of view (FOV) is determined by the size of a single antenna and by the observing frequency, but is independent of the array configuration. The FOV is expressed in terms of the primary beam, which describes the antenna response (sensitivity) as a function of the angle away from the main axis. At 300 GHz, the FWHM of the ALMA primary beam is 17″; this parameter scales linearly with wavelength.

In interferometry, the signals of all individual antennas that make up an array are combined, or correlated, in order to simulate an observation with a single-dish telescope that has the size of the array. It is important that all signals have the same phase, otherwise the correlated signal will have no output. Very careful timing of, and correction for, the delay with which signals from different antennas are combined is thus of the essence. Water vapour in the atmosphere slows down the propagation of the signals, making them arrive slightly later than they would have without water in the atmosphere. This is especially problematic if the distribution of water vapour is non-uniform (and thus varies from antenna to antenna). Furthermore, the amount of water vapour varies with time. Observations in the (sub-)mm regime are particularly susceptible to this, especially at the high-frequency range. Therefore, in order to successfully correlate the signals from the various antennas, one has to know the amount of water vapour in the atmosphere. This is achieved by using a “water vapour radiometer”, which is installed at every antenna, and monitors the amount of water vapour in the atmosphere by measurements at 183 GHz. These data are then used to correct for the delay in the arrival times of the signals.

4. ALMA science goals

The design of ALMA and the technical specifications outlined in the previous section, are based on three main key science goals:

1. the ability to detect spectral line emission from CO and CII in normal galaxies at redshift $z = 3$ in less than 24 hours of observation;
2. the ability to image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars at a distance of up to 500 light years, to study their physical, chemical, and magnetic field structures, and detection of the tidal gaps created by planets undergoing formation in the disks;
3. to provide images at an angular resolution of better than $0.1''$, and at high dynamic range.

In addition to these three main key science goals, other important topics will be explored with ALMA, such as:

- redshifted dust continuum emission from evolving galaxies at epochs of their formation as early as z = 10. The inverse K-correction will make ALMA the ideal instrument for investigating the origin of the galaxies in the early Universe, with confusion minimized by the high spatial resolution;
- CO emission to derive the redshift of star-forming galaxies;
- cold dust and molecular gas in nearby galaxies to study the interstellar medium in different galactic environments, the effect of the physical conditions on the local star formation history, and galactic structure;
- kinematics of obscured AGN and quasars on spatial scales of 10-100 pc, to test unification models of Seyfert galaxies;
- dynamics of the molecular gas at the centre of our own Galaxy with unprecedented spatial resolution revealing the tidal, magnetic, and turbulent processes;
- detailed analysis of how stars form from the gravitational collapse of dense cores in molecular clouds, and of the formation and evolution of disks and jets in young protostellar systems;
- formation of molecules and dust grains in the circumstellar shells and envelopes of evolved stars, novae, and supernovae;
- refinement of dynamical and chemical models of the atmospheres of planets in our own Solar System, and imaging of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper Belt Objects.

The Italian astronomical community has strong interests in several of these lines of research.

5. Early Science observations

At the moment of writing (October 2010) there are 8 antennas at the AOS, and new antennas and receivers will follow at regular intervals. It will not be necessary to wait for all 66 (50+16) antennas to be at the AOS to do science. When certain minimum requirements are met, the project enters into its next phase, that of Early Science.

Early Science can be done when the following conditions apply:

- at least 16 12-m antennas fully commissioned;
- array configurations sufficient to cover the shortest spacings and out to a maximum baseline of 250 m (but hopefully 1 km);
- at least three frequency bands on each antenna (hopefully four: bands 3, 6, 7, and 9; possibly plus bands 4 and 8 on as many antennas as possible);
- single-field interferometry observing mode (and hopefully interferometric pointed mosaics);
- a mixture of continuum and spectral line correlator configurations;
- calibration to a level already achieved on established mm arrays;
- tools required for proposal submission, preparation and execution of observations, and data reduction are in place.

The decision to issue a Call for Proposals for Early Science will be made when it is likely that the above-listed requirements will be met within the next eight months. This Early Science Decision Point (ESDP) is expected to be early December 2010. The deadline for submitting proposals will be two months after the ESDP and observations will begin six months after that.

In general, when the Joint ALMA Office (JAO) issues calls for proposals, an astronomer who wishes to apply for observing time, will have to register on the ALMA web page. The proposal will be prepared with the ALMA Observing Tool (AOT). The AOT, a java application, is a software package to construct a proposal, called Observing Project. This Observing Project consists of two parts: a Phase I Observing Proposal containing the scientific justification of the proposed observations and a minimal amount of technical information required to check the feasibility of the proposal, and a Phase II Observing Programme, to be submitted only if observing time has been granted. The JAO, with assistance from the ALMA Regional Centres (ARCs) [see Sect. 6], coordinates the refereeing process of the submitted proposals. There will be a single Time Allocation Committee.

In the case of a successful proposal, the user will be required to prepare the Phase II programme, providing full details of the proposed observations. The user will not travel to Chajnantor to carry out the observations, but the programmes will be entered into a queue to be dynamically scheduled, depending on requested weather conditions and array configuration. The data obtained will pass through a quality assurance programme (such as on-site checks by the astronomer-on-duty, a quick-look analysis, system performance checks), will then go through the data reduction pipeline, and be delivered to the archive. P.I.'s of the proposals will be notified immediately after their data become available. They will receive the pipeline products, such as fully calibrated images or data cubes, and calibrated u-v data.

The ALMA data will be reduced with the Common Astronomy Software Applications package, better known as CASA. CASA has been developed with the primary goal to support the data post-processing needs of the next generation of radio telescopes, such as ALMA but also the Expanded Very Large Array (EVLA). CASA can process both interferometric and single-dish data, and is developed by an international consortium led by the National Radio Astronomical Observatory (NRAO). CASA consists of a set of C++ tools bundled together under an iPython interface as a set of data reduction tasks. This structure provides flexibility to process the data via a task interface or as a python script. In addition to the data reduction tasks, many post-processing tools are available for even more flexibility and special purpose reduction needs. CASA is currently in Beta (3.1) release, and a Cookbook and Reference Manual are available from the NRAO CASA web site (http://casa.nrao.edu/).

6. The Alma Regional Centre network

ALMA is intended to be an instrument for which even a non-expert in mm-interferometry should be able to write a successful proposal. Much attention is therefore given to user support. The interface between ALMA and the user community is managed by three ALMA nodes, called ALMA Regional Centres (ARCs), located in Europe, North America, and East Asia. The European ARC is at ESO, Garching, and serves as the access portal to ALMA for the European user community. The EU ARC manages a network of local European ARC nodes, which provide additional services to the whole of the EU community. The details of the responsibilities of the various partners in the network are described in a Memorandum of Understanding. The European ARC-nodes are located at Bonn-Bochum-Cologne (Germany), Bologna (Italy), Onsala (Denmark, Sweden, and Finland), IRAM-Grenoble (France), Leiden (The Netherlands), Manchester (United Kingdom), and Ondrejov (Czech Republic). The support offered by the ARCs to the user community includes:

- archiving and data reduction support, such as face-to-face data processing support, modified pipeline versions, re-processing of large and/or complex datasets, simulation development, and help with archival research projects;
- support for special projects, such as public surveys;
- science community development, such as support for ALMA research, post-doctoral fellowships, and specialized schools and workshops.

Each local ARC node contributes with its own specific expertise, in order to ensure that maximum advantage of the European competences in the field of (sub-)mm interferometry is taken. More information on the European ARC network is available on the web pages http://www.eso.org/sci/facilities/alma/arc/, where links to its North American and Japanese counterparts can also be found.

6.1. The Italian ARC

The Italian ARC-node is hosted by the Istituto di Radioastronomia in Bologna, and is funded by INAF. When ALMA is operational, the ARC-node will have 1 staff-member and 4 post-docs that spend about 50% of their time to provide user support, including face-to-face help, and a system manager who takes care of the software and hardware of the ARC (which has a dedicated server), and in particular with the development of the of GRID technology. Furthermore, from October 2010 an ESO-ALMA Fellow will join the ARC for 3 years, who will be especially involved with the scientific part of the preparation of programmes for Early Science. The members of the Italian ARC are experienced in the reduction of interferometric data with CASA and in the use of the AOT. They regularly participate in tests of the various software packages, organized on an international level. To inform the astronomical community we regularly organize so-called ALMA-days, in which updates are given of the ALMA project and experts are invited to talk about the impact of ALMA on various fields of research. To instruct the community in the use of the CASA data reduction package we have recently organized a CASA-tutorial. In the Summer of 2011 the ARC will organize, in collaboration with the EU COST-Action network, an international school on “Astrochemistry with ALMA”.

When ALMA users need assistence in preparing observing proposals, when they require support with the reduction of their data (if the pipeline products are not to their satisfaction), then they can contact the central helpdesk at ESO, which will then either answer the questions or direct the user to one of the ARC nodes if specialist help is required. The various nodes in the EU-ARC network have particular areas of expertise, and provide face-to-face help to users who require this. The Italian ARC offers specialized help with polarimetry, mosaicking, and the handling of large data sets. Around the time of the Call for Proposals for Early Science a “Guide to the European ARC” will be published, which details the type of support offered, and how to get access to it. For more information please visit our website http://www.alma.inaf.it.

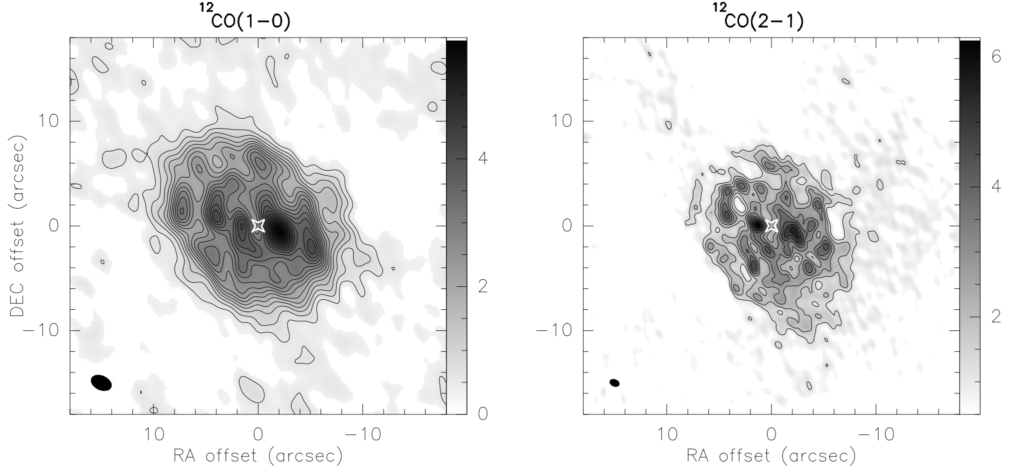

Fig. 1. *Left panel*: ^{12}CO(1–0) integrated intensity contours observed with the IRAM PdBI+30-m towards the centre of NGC 5953. The white star marks the coordinates of the dynamical centre of the galaxy, with offsets in arcseconds. The map, derived with 2σ clipping, has not been corrected for primary beam attenuation. The *rms* noise level is $\sigma = 0.09\,\mathrm{Jy\,beam^{-1}\,km\,s^{-1}}$ and contour levels run from 3σ to 21σ with 3σ spacing. In this map a $\pm130\,\mathrm{km\,s^{-1}}$ velocity range is used. The beam of $2\farcs1 \times 1\farcs4$ is plotted at lower left. *Right panel*: Same for ^{12}CO(2–1). The *rms* noise level is $\sigma = 0.2\,\mathrm{Jy\,beam^{-1}\,km\,s^{-1}}$ and contour levels run from 3σ to 10σ with 3σ spacing. The beam of $1\farcs1 \times 0\farcs7$ is plotted at lower left. Figure from Casasola et al. (2010).

7. An example of science in preparation of ALMA

In this section, we discuss a specific ALMA science case, the AGN fueling, its state of the art, and what we will learn about this topic with ALMA. Identifying the main mechanism responsible for fueling AGN has been one of the hottest topics in the last decade. Non-axisymmetric potentials introduced by stellar bars and galaxy interactions were considered as promising mechanisms for fueling local low-luminosity AGN (LLAGN). CO observations offer the possibility of directly witnessing the gas fueling towards the nucleus. Observational campaigns have been performed with millimeter instruments to investigate this issue: the NUclei of GAlaxies (NUGA) survey, performed with the IRAM Plateau de Bure Interferometer (PdBI) and dedicated to a sample of 12 nearby LLAGN, found that these objects are characterized by a wide variety of molecular gas distributions (e.g., streaming motions along stellar bars, rings, nuclear concentrations, nuclear voids, and irregular distributions), and that sometimes the gravitational torques exerted by the stellar potential on those gas distributions can fuel the central AGN (e.g., García-Burillo et al. 2003; Combes et al. 2004; Casasola et al. 2008, 2010). This suggests that several mechanisms, rather than a single universal one, can cooperate to fuel the central engines of LLAGN.

Fig. 1 shows ^{12}CO(1–0) and ^{12}CO(2–1) integrated intensity distributions obtained for the interacting Seyfert 2/LINER galaxy NGC 5953 by combining IRAM PdBI and single-dish 30-m observations, in the context of the NUGA project. The CO emission is distributed over a disk of diameter of $\sim16''$. Our ^{12}CO(1–0) observations show several peaks, distributed more or less randomly, with the strongest one offset from the nucleus by $\sim2''$. In the ^{12}CO(2–1) map the central emission is also clearly resolved and more clumpy than in ^{12}CO(1–0). The strongest ^{12}CO(2–1) peak is not that at $\sim$2-3$''$ to the W/SW from the nucleus, like for ^{12}CO(1–0), but that at $\sim1\farcs5$ E from the nucleus.

High-resolution optical and near-infrared images of galaxies allow one to quantify the efficiency of the stellar potential in draining angular momentum in a galaxy by deriving torques exerted by the potential on the gas. In NGC 5953, we found that the torques are predominantly positive in both ^{12}CO(1–0) and ^{12}CO(2–1), suggesting that gas is not flowing into the centre. This comes from the regular and almost axisymmetric total mass and gas distributions in the centre of the galaxy. In NGC 5953, the AGN is apparently not being actively fueled in the current epoch.

The results obtained from the analysis of stellar torques in NUGA galaxies have revealed a puzzling feeding budget in the circumnuclear disks. Paradoxically, feeding due to the stellar potential seems to be presently inhibited close to the AGN for the ~50% of the analyzed galaxies. García-Burillo et al. (2005) suggest that gravitational torques could be assisted by other mechanisms, such as the viscosity, that become competitive with non-axisymmetric perturbations. Gravitational torques and viscosity could combine to produce recurrent episodes of activity during the typical lifetime of any galaxy. Concerning the AGN fueling, ALMA will allow us to improve the statistics of the AGN surveys, by increasing the size of galaxy samples by orders of magnitude. The typical ALMA spatial resolution will provide a sharp view of the distribution and kinematics of molecular gas in the central pc of nearby AGN. Moreover, local AGN have low luminosity and do not require high fueling rates from the host galaxies: for most local Seyfert nuclei black hole accretions rates are of $\sim 10^{-3}\,M_\odot\,yr^{-1}$, and at these rates a single molecular cloud of $10^6\,M_\odot$ can keep the nuclear activity going for ~1 Gyr. The fueling problem becomes more serious for high-luminosity AGN, like radio galaxies and quasars, whose black hole accretions rates may be $>1\,M_\odot\,yr^{-1}$. Quasars are much more distant than Seyfert galaxies, and the limited sensitivity and angular resolution of the current millimeter interferometers do not allow us to map the molecular gas distribution in quasars, except for a few cases. With ALMA, instead, we will easily map the gas in quasar hosts.

ALMA will allow us to analyze in detail the bar/AGN feeding cycles of distant galaxies and to compare fueling mechanisms as a function of redshift. ALMA will deepen our understanding of how stars form and how star formation and AGN fueling processes interact. Finally, we will be able to perform Galactic-scale science in distant galaxies.

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