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ALMA: Science with exceptional submillimeter capabilities.

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Abstract

The Atacama Large Millimeter/submillimeter Array (ALMA) is an outstanding facility for millimeter and submillimeter-wave Astronomy with transformational capabilities to study the origin of galaxies, stars, and planets. ALMA consists of sixty six antennas located on the Chajnantor plateau at five thousand meters altitude in northern Chile, and equipped with receivers covering atmospheric windows between 30 and 950 GHz. ALMA is an international partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. Since its third Call for Proposals ALMA received more submissions than any other telescope in history, surpassing 1800 proposal in the latest Call for Cycle 6.

1 Introduction

The Atacama Large Millimeter/submillimeter Array consists of sixty-six high precision antennas working in interferometric mode at millimeter/submillimeter wavelengths at 5000 m height close to San Pedro de Atacama, in the north of Chile.

It is composed by a big array of fifty antennas with twelve meter diameter (called 12-m array), and a smaller one (called Morita Array) with twelve antennas of seven meter plus four antennas of twelve meters diameter to recover extended emission from astronomical sources. The 12-m array is movable from compact to very extended configurations (baselines from $\simeq 150$ m up to $\simeq 16$ km) to achive different spatial resolutions, ranging from $\simeq 5''$ to $\simeq 0.04''$ at 110 GHz and to $\simeq 0.5''$ to $\simeq 0.0044''$ at 950 GHz. Thanks to the interferometry technique we can see detailed images in field of views of $\simeq 70''$ at 3.5 mm to $\simeq 7''$ at 315 μm. ALMA operates in eight different bands (band 3 to band 10) from frequencies between 84 to 950 GHz respectively.

Signals from different antennas are combined in a very powerful supercomputer, the

ALMA correlator, characterized for being a very flexible machine that allows simultaneous high and low spectral resolution observations (Fig. 1). ALMA has a bandwidth of 8 GHz and up to 7680 frequency channels, providing a very high sensitivity in the continuum and very high velocity resolution.

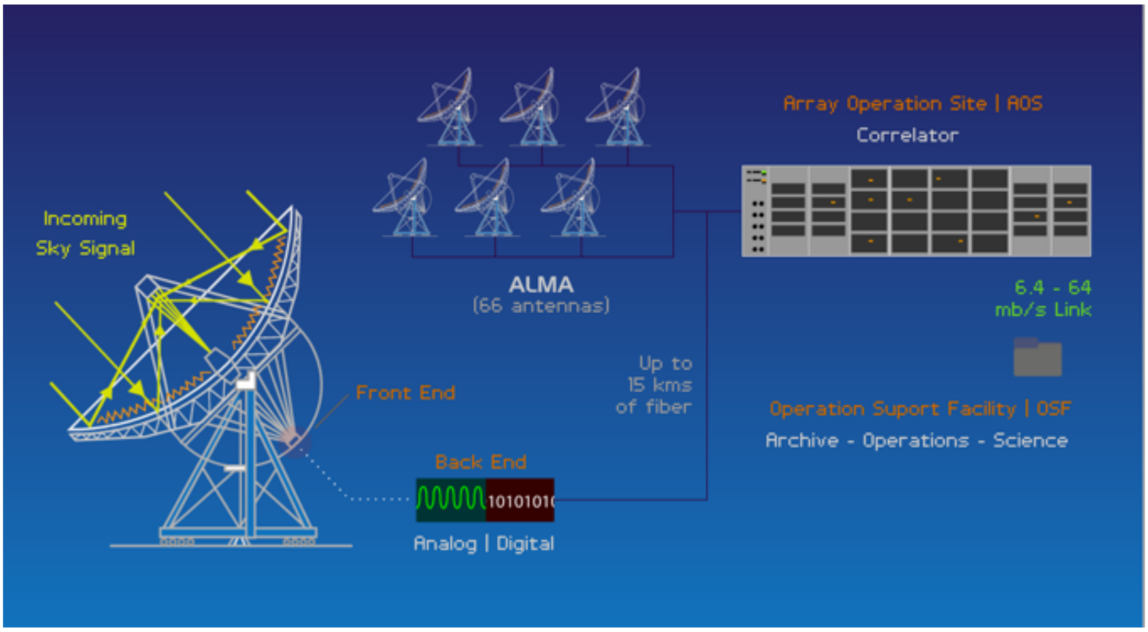

Figure 1: ALMA signal combination. Courtesy: ALMA(ESO/NAOJ/NRAO)

1.1 Submillimeter Astronomy

ALMA is capable to study the part of the electromagnetic spectrum in between the far infrared and the radio waves, observing the light comming from very cold objects. At submillimeter wavelengths we mainly see thermal continuum emission from cold dust, and spectral lines from molecular gas that yield information on the physical conditions, chemistry and kinematics.

Many objects produce emission in the millimeter/submillimeter regime: from Solar System objects, molecular clouds, star forming regions, protoplanetary disks, and evolved stars, to nearby and very distant galaxies. ALMA allows us for the first time to study at high angular resolution and high sensitivity the properties of dust and gas in a wide range of sources from the local to the very distant Universe.

1.2 The ALMA site: 5000 m height in the Atacama Desert

The Atacama Large Millimeter Array is located at five thousand meters height in Llano Chajnanator, a plain in the middle of the Atacama desert very close to San Pedro de Atacama, in Northern Chile (see Fig. 2). This place was selected to host the ALMA antennas because

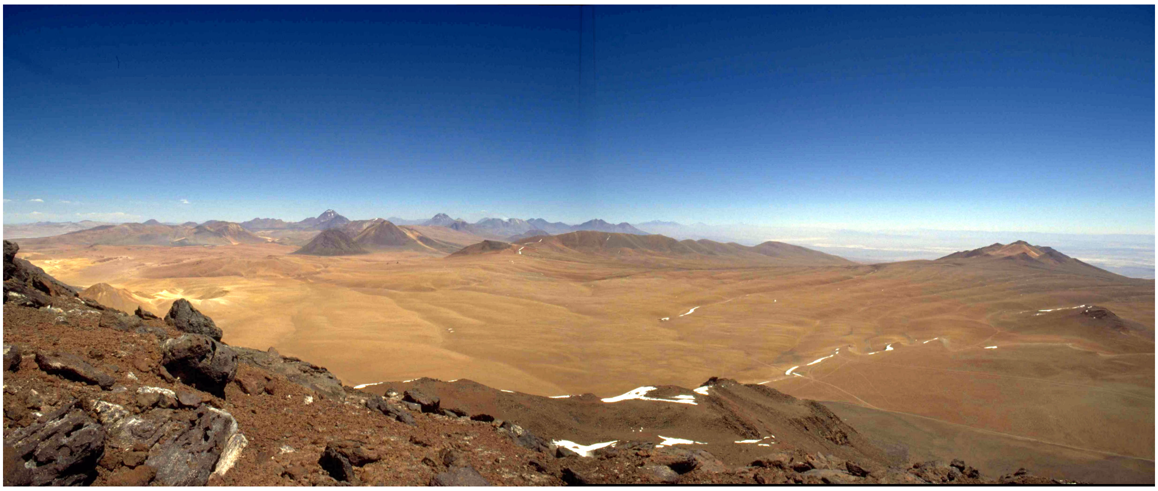

Figure 2: ALMA site in 1994. Courtesy: S. Radford

it possesses very good conditions to carry out sucessfully interferometric observations in the submillimeter/millimeter regime in terms of atmospheric transparency and stability.

Inhomogeneities in the distribution of the water vapor in the atmosphere cause variations in the electrical path length of the incoming signal, which induces larger phase errors degrading the sensitivity and the spatial resolution of interferometric images. The high altitude of Llano Chajnantor reduces the thickness of the atmosphere above the observatory, and the very dry air of the desert helps to decrease the absorption of the incoming radiation by the trophosferic water molecules.

2 ALMA science operations

ALMA is an international partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. There are more than twenty countries contributing to ALMA. Chile is the host country and Chilean astronomers can access to the 10% of total observing time to carry out their own research.

ALMA science operations is led by the Joint ALMA Observatory in Chile, and the ALMA Regional Centers (ARCs) from Europe (led by the European Southern Observatory), North America (led by the National Radioastronomy Observatory), and from East Asia (led by the National Astronomical Observatory of Japan), see Fig. 3.

The Joint ALMA Observatory provides array operations, scheduling of projects, execution of observations, data quality assurance and trend analysis, calibration plan maintenance, delivery of data to the archives, archive operations, pipeline operations, and software subsystem scientists. The ARCs are the interfaces to the user community and as core tasks they provide user support (via helpdesk and face to face), delivery of data to the principal investigators of scientific projects, mirror archive operations, astronomers on duty, subsystem scientists, and data quality assurance.

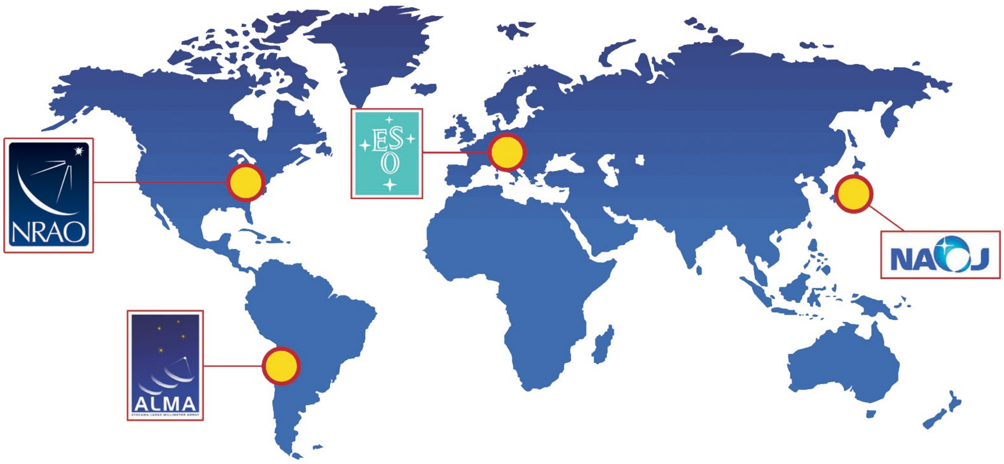

Figure 3: ALMA Science Operations Centers. Courtesy: ALMA(ESO/NAOJ/NRAO)

The Joint ALMA Observatory is composed by three different places: The Operations Support Facility (OSF; where the technical building and the Residencia are located), the Array Operations Site (AOS; with the antennas, correlator, local oscilator and fiber optics network), and the Santiago central Offices (SCO; where the main archive, data transmission to the ARCs, and the offices for Science, Computing, Administration and Management are located).

2.1 From the Call for Proposals to the observations

ALMA Call for proposals is announced once per year through the ALMA Regional Centers. All information and documentation is presented at the ALMA Science Portal. Every year Europe and North America access to 33.75% of the total observing time each, East Asia to 22.5%, and Chile as host country receives 10% of the available time. Users can send their proposals through the ALMA Observing Tool (Phase 1).

Afterwards all proposals go through the ALMA Proposals Review Process, where several ALMA Review Panels of different scientific areas provide the science assessment. The technical feasibility of projects are checked by scientific personnel at the Joint ALMA Observatory. Proposals are ranked and graded in the review panels meeting. A merge of all panels outputs is made by a committee composed by the panels chairs, where the final rank is produced.

In a second step the Joint ALMA Observatory evaluates the scheduling feasibility of the proposals, fine tune the configurations periods, and adjusts grades of proposals to have an homogenous distribution of proposals pressure per LST and per configuration. The approved proposals will be admitted to produce observing files (Phase 2).

2.2 High-level concepts for ALMA Science Operations

Observations at ALMA are done in service mode at the Operations Support Facily. Scientific ALMA staff from the JAO and from the ARCs carry out those observations using a dynamic scheduling. All science observations are executed in the form of scheduling blocks, each of which contains all information necessary to schedule and execute the observations. The Scheduling Blocks are repeated until the rms requested by the Principal Inverstigator of a proposal is reached. All science and calibration raw data are captured and archived and, by default, calibrations are done with a dynamic query. The default output to the astronomers are processed images, calibrated by the ALMA pipeline in the case of standard observing modes or by ALMA staff in the case of non standard observing modes.

The JAO in Chile is responsible for the data product quality and the Users Support is done at Regional Centers level, face to face or through the ALMA helpdesk system.

2.3 ALMA capabilities offered in Cycle 6

Along the six years that ALMA has been operating, commissioning activities and science observations of accepted projects ran in parallel. In Cycle 6 ALMA offered at least fourty three antennas in the 12-m Array movable into ten different configurations with maximum baselines from 160 m to 16 km. In the Morita Array ten seven meter antennas are ready for recovering extended emission, and three twelve meter antennas for making single-dish maps. Eight different receivers are offered from band 3 to band 10. Bands 8, 9 and 10 can be used with maximum baselines up to 3.6 km, band 7 up to 8.5 km , and bands 3, 4, & 6 up to 16 km.

Spectral line and continuum observations with the 12-m Array and the Morita Array are possible in all bands, as well as single field interferometry. Mosaics can be done in Bands 3 to 9 with the 12-m Array and the Morita Array. Single dish spectral line observations can be done in Bands 3 to 8.

In Cycle 6 on-axis and single-pointing polarization capabilities are offered. Full (linear and circular) polarization observations for continuum are possible with full spectral resolution observations in Band 3 to 7 on the 12-m Array. In this Cycle Solar observations and VLBI proposals are offered in continuum mode for Bands 3 and 6.

In relation to the proposals types, principal investigators can submit regular proposals, Large programs, Target of Opportunity (ToO), and time constrains projects.

3 Science with ALMA

The Fundamental Science Drivers that inspired the construction of ALMA, as detailed here, are:

- 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 protoplanetary disk at a distance of 150 pc, 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 $0.1''$.

Given the current status of the array we can say that all the scientific goals that provoked the construction of ALMA have been now achieved.

Since the very first observations ALMA has contributed to the advance of knowledge in many different fields, providing high impact publications and excellent data for doing transformational science (see Fig. 4).

Figure 4: The first ALMA press releases. Courtesy: ALMA(ESO/NAOJ/NRAO)

In the field of Extragalactic Astronomy (see Fig. 5) ALMA was able to measure the mass of a black hole with extreme precision in NGC 1332 using the CO(J=2-1) spectral line transition [3], as well as to yield the sharpest view ever of star formation in the distant Universe through the high spatial resolution image of the gravitationally lensed galaxy SDP.81 [8].

In the evolved stars framework ALMA showed spectacular images of a Gaseous spiral-shell pattern characteristic of elliptical binaries in LL Pegasi [5] (see Fig. 6), and it shed light into the formation of multiple systems by caughting in act of forming close multiple young stellar objects via disk fragmentation in L1448 IRS3B [12].

ALMA, for the first time is providing high spatial resolution and sentivity to observe Solar System objects in millimeter/submillimeter wavelegths confirming the complex chemistry in Titan's atmosphere by detecting vinyl cyanide molecule [7].

One of the science topics where ALMA has provided transformational science is in the field of protoplanetary disks and planet formation, where studies of the dust temperature distribution and nature of dust particles, as well as high angular resolution observations of

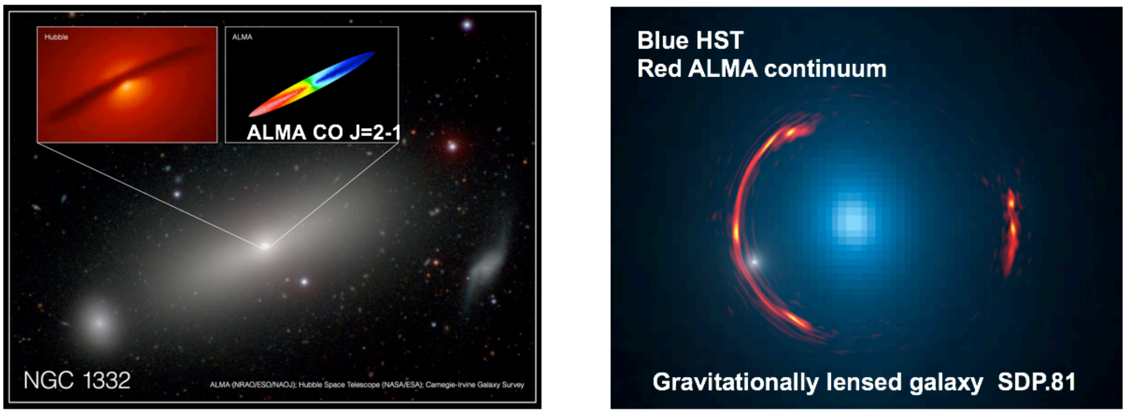

Figure 5: Left: Kinematics surrounding a black hole in NGC 1332 [3]. Right: continuum emission from the gravitationally lensed galaxy SDP.81 [8] . Courtesy: ALMA(ESO/NAOJ/NRAO)

the gas dynamics are now possible with unprecedented detail. As a few examples, ALMA was capable to show planet formation in Earth-like Orbit around the young Sun-like star TW Hydrae [1], cavities and spiral arms in MWC 758 [4] (see Fig. 6), and the discovery of a trio of infant planets around newborn stars [9], [11].

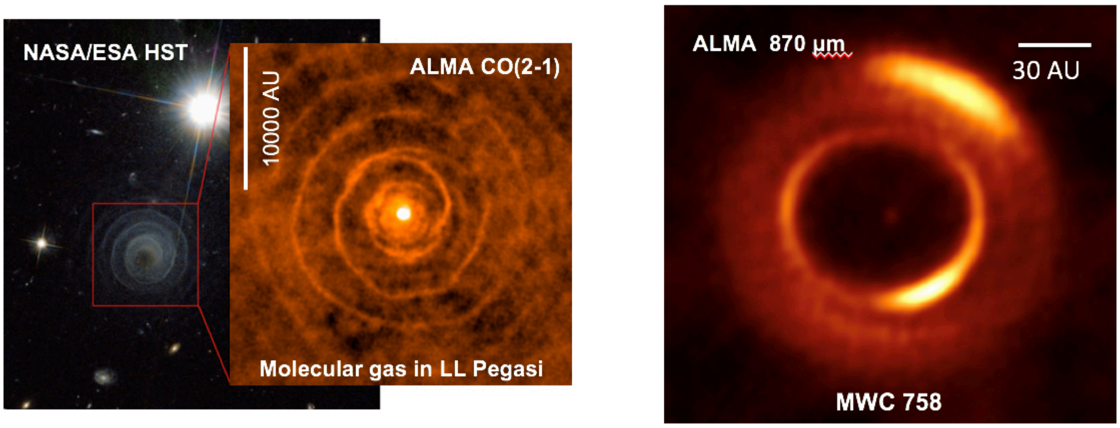

Figure 6: Left: Spiral shell pattern seen in molecular in LL Pegasi. Right: detailed dust structures in the disk surrounding MWC 758 [5]. Courtesy: ALMA(ESO/NAOJ/NRAO)

Recently ALMA discovered cold dust around the nearest star Proxima Centauri [2]. And in the Astrochemistry and Astrobiology fields ALMA is also giving new insights, like the detection of the first extragalactic hot molecular core in the Large Magellanic Cloud [10], or the first detection of the prebiotic complex organic molecule Methyl Isocyanate, involved in the synthesis of peptide and amino acids, in a solar-type Protostar [6].

Observations of the Sun are now possible with ALMA and since Cycle 4 ALMA has become part of the global VLBI networks operating in the millimeter and submillimeter, working at 3 mm in conjunction with the Global Millimeter VLBI Array (GMVA), and at 1.3 mm in conjunction with the Event Horizon Telescope (EHT) network (to observe nearby supermassive black holes).

4 Future of ALMA

While ALMA is achieving its Full Operations state, the commissioning of some observing modes still needs some work to be finished, like:

- High frequencies observations for long baselines, Solar, single-dish, Compact Array standalone, and polarization.
- Phased Array (VLBI) mode to support observations in spectral lines and pulsars.
- Single-dish observations in continuum and at high frequencies.
- Wide field polarization mode.
- Improved observing efficiency.

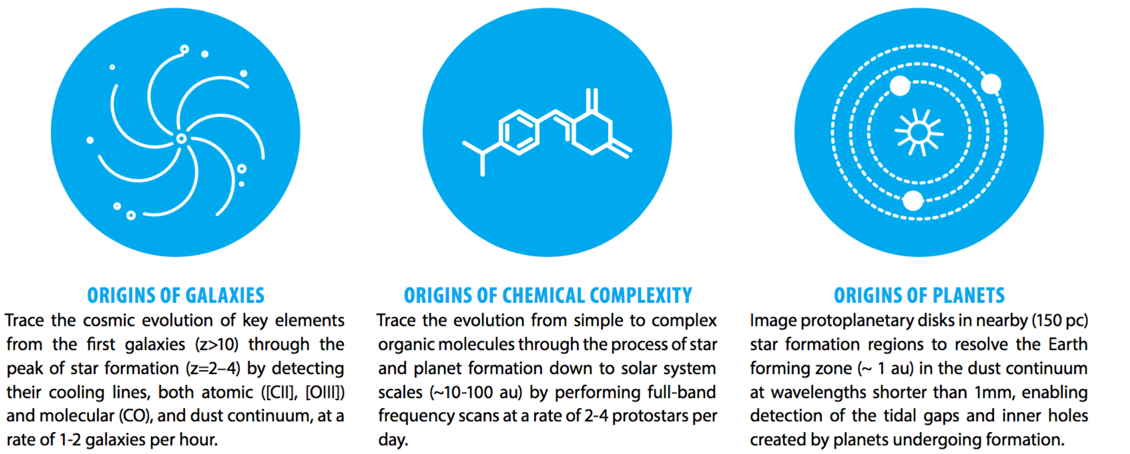

Figure 7: Fundamental science drivers for ALMA developments over the next decade. Courtesy: ALMA(ESO/NAOJ/NRAO)

There is a development plan to improve ALMA future capabilities, which is a three-years cycle of studies that can be software or hardware oriented. First calls went out in 2010, 2013, and 2016. Thanks to these programs the Band 5 was offered in Cycle 5 and ALMA VLBI observations could be offered from Cycle 4. Development programs will also provide improved receivers: a Band 2 + Band 3 prototype is on-going, a Band 7/Band 9 upgrade will come soon, and the Band 1 is expected to be ready for Cycle 8.

Very recently the ALMA development working group set new science drivers that will lead new development of ALMA until 2030 for the next decade (Fig. 7) The main drivers will focus into the study of the origins of galaxies, origin of chemical complexity, and the origin of planets. For that the receivers, the digital systems, and the correlator must be upgraded. The ALMA archive will be further developed using data mining tools to exploit it.

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