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The Joint ALMA Observatory: brief history and first scientific results

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Abstract

ALMA is the more sophisticated and multinational astronomical observatory ever installed on the Earth's surface. Scientific observations with ALMA started on September 2011 as the cycle 0 of Early Science, with an instrument limited in its number of antennas and receivers, but fully competitive with similar existing instruments. Currently the first observational results are being published. Meanwhile, the ALMA construction proceeds in Chajnantor (Chile), at an altitude of 5000 m. In this paper we will briefly describe the history, first scientific results and future capabilities of ALMA, an observatory that will be essential in many fields of astrophysics for decades to come.

1 Introduction

The Atacama Large Millimeter/submillimeter Array (ALMA) has been qualified as the humanity's most complex ground-based astronomical observatory to date. On September 2011 ALMA officially started scientific operation, a first round of scientific observations known as Early Science Cycle 0. Meanwhile, the ALMA technical and scientific team was still busy testing the observatory's systems ([14]), adding new antennas and capabilities to the instrument ([8]), and delivering new data sets to the astronomical community obtained with a small number of antennas, to show what can be expected. The first scientific results are being published, most of them based in this sort of preliminary data. A full description of the observatory is given by [7].

In mid July 2012 forty antennas (out of a total of 66) had been processed by the AIV and CSV teams, most of them were located at the Array Operations Site (AOS) in Chajnantor (cf. Fig. 1). About twenty additional antennas were in the process of assembly, integration and technical and scientific verification at the Observatory Support Facility (OSF). Some Cycle 0 data sets had already been delivered to the Principal Investigators of the approved proposals. The deadline for Early Science Cycle 1 was set to the date this talk was given in

Figure 1: Recent picture showing more than 30 antennas at the Array Operations Site. Courtesy of C. Padilla (NRAO) and ALMA/NRAO/ESO/NAOJ.

the special SEA session devoted to ESO[1]. New scientific results were expected to be shown in several workshops and conferences planned for the second half of the year, in spite of the data being delivered more slowly than expected by the researchers. The full ALMA array was expected to be completed by the end of 2013, the antennas being equipped with a subset of receiver bands. Future technical developments are expected after the baseline ALMA is build, e.g. filling in missing receiver bands.

2 The need for ALMA

Millimeter-wave interferometry has developed since ∼1985. Several instruments were build, with a limited number of antennas (6 in the OVRO, NRO and Plateau de Bure arrays, 9 in the BIMA array) and a limited frequency range, usually 85 – 250 GHz (cf. [25] and references therein). The submillimeter interferometry started in 1992 with seminal experiments in Mauna Kea using the CSO and JCMT antennas ([3]), that in 2004 lead to the SMA, an array of eight 6-m antennas that operates at frequencies from 180 to 700 GHz ([10]). The limitations of these instruments are the insufficient sensitivity (collecting area < 1000 m^2), slow mapping (tens of baselines, limited range of simultaneous baseline lengths therefore often requiring several configurations), low fidelity (sensitive to a very limited range of spatial scales), insufficient angular resolution (down to $0\farcs13$ in CARMA) and limited spectral coverage. Progress in mm/submm receiver performance and bandwidth, in antenna design (including sophisticated metrology) and in digital electronics, required to build a versatile correlator able to process thousands of channels for thousands of baselines, lead to several

[1]Finally, 1132 proposals were submitted by 2836 astronomers around the world, a 23% increase in number of proposals compared to Cycle 0.

projects meant to overcome (some of) the previous limitations: LMA in Japan, MMA in the USA and LSA in Europe. Finally they converged in a unique, larger scale project meant to overcome all the mentioned limitations. An exceptional site (high and dry) was chosen, the 5000 m high plateau of Chajnantor in the Atacama desert, hence the final name of Atacama Large Millimeter/submillimeter Array (ALMA).

The first step was the merging in 1997 of the LSA and MMA projects in a 50-50 partnership between Europe and the USA, and the establishment of a joint direction. The plan was to install 64 12-m antennas (later on reduced to 50 antennas) at the submm quality Llano de Chajnantor. In the next few years ESO and several national institutions provided funds for the project, leaded by an European Coordination Committee. In 2003 Spain and Canada officially joined the project, and tests of prototype antennas started at the VLA site. In 2004 Japan joined the project, providing a compact array of four 12-m antennas and 12 7-m antennas, and Taiwan did so in 2005. Since 2006, ALMA is a partnership of Europe (32.5%), Japan (25%) and North America (32.5%), in cooperation with Chile (10%). ALMA is funded in Europe by ESO, in Japan by NINS in cooperation with the Academia Sinica, and in North America by the US NSF in cooperation with the NRC. The details of the participation of ESO in ALMA can be followed in several articles in The Messenger. The international conference "Science with ALMA: a new era for Astrophysics" was held in Madrid (Spain) in 2006. Over 300 participants exchanged views about preparatory observations and the best science that could be done with ALMA [1]. The first antenna reached the OSF in 2007. The first interferometric observation with 3 antennas at the AOS was carried out in November 2009.

3 First scientific results

Almost half of the proposals approved for the first round of observations corresponded to the study of interstellar matter and the formation of stars and planetary systems. Several papers have already been published on this subject to date (July 2012), most of them based on publicly available commissioning and science verification data (hereafter, CSV).

The study of TW Hya by [18] has implications on the study of the physical and chemical history of the solar system. TW Hya is the best studied protoplanetary disk because of its near face-on viewing geometry and its proximity, at 51 pc this is the T Tauri star closest to the Sun. With a mass similar to the Sun and a much younger age, of about 10 million years, it is surrounded by a cold circumstellar disk of gas and dust about 200 AU in diameter. It was observed with ALMA in three bands by an array of eight antennas in order to map the distribution, kinematics and abundance of a series of molecules, including CO and HCO^+. Öberg et al ([18]) realized that the DCN 3-2 emission was also detected in the CSV data, with a SNR an order of magnitude higher than SMA data published by [22], and similar to the stronger DCO^+ 3-2 emission also detected with the SMA. In spite of their similar critical densities, their distributions strongly differ. DCN shows a centrally peaked distribution, in contrast to DCO^+, which shows an increasing column density with radius. This was interpreted as DCN forming at a smaller radii than DCO^+, consistent with chemical model predictions of DCN formation at higher temperatures. This immediately suggests the

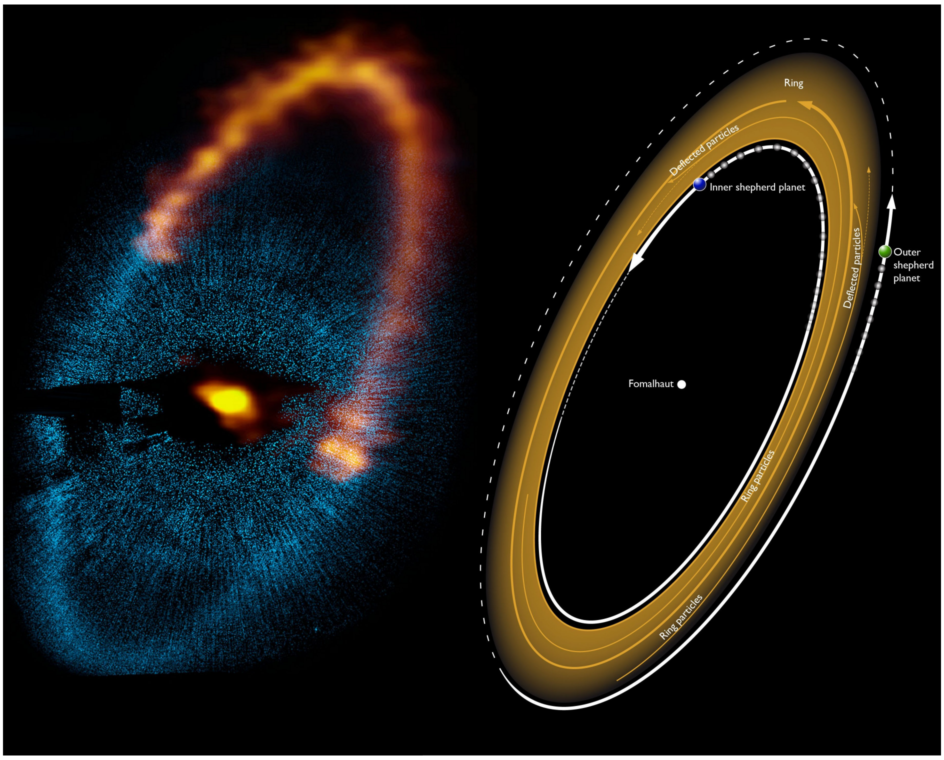

Figure 2: *Left panel*: Overlay of the optical (HST, in blue) and radio (ALMA, in amber) of the narrow ring around Fomalhaut. *Right panel*: Diagram showing the best explanation found for the observational results. Courtesy of STScI/NASA/ESA, ALMA/NRAO/ESO/NAOJ and B. Saxton (NRAO).

presence of different formation pathways for these species, and stresses the need to obtain spatial distributions, for which ALMA is the right instrument, to put stronger constrains on aspects of chemical evolution other than simple abundance ratios. In addition to that, the multiple pathways found for deuteration enhancement may challenge the conventional wisdom that the high deuterium abundance in comets imply a simple, cold chemical history for the solar system body formation.

The bright young star Fomalhaut is closer (7.7 pc) and older (around 200 million years) than TW Hya, but it is still surrounded by a thin debris ring, as observed in scattered optical light by [13]. According to these optical observations, the micron-sized dust grains are distributed in a belt 25 AU wide, with a very sharp inner edge at a radial distance of 133 AU, and an eccentricity of 0.2 (Fig. 2). Consequently, the presence of a shepherd planet orbiting the inner part of the ring was inferred. Observations of millimeter-sized grains, less affected by stellar radiation, can trace more accurately the signatures left by the dynamical evolution of planetary systems. [2] measured the 350 GHz (0.850 mm) radio continuum emission of the upper half of the Fomalhaut debris ring with $1''.3$ angular resolution. The ALMA observations show that the ring is ~ 16 AU wide with sharp inner and outer boundaries. A

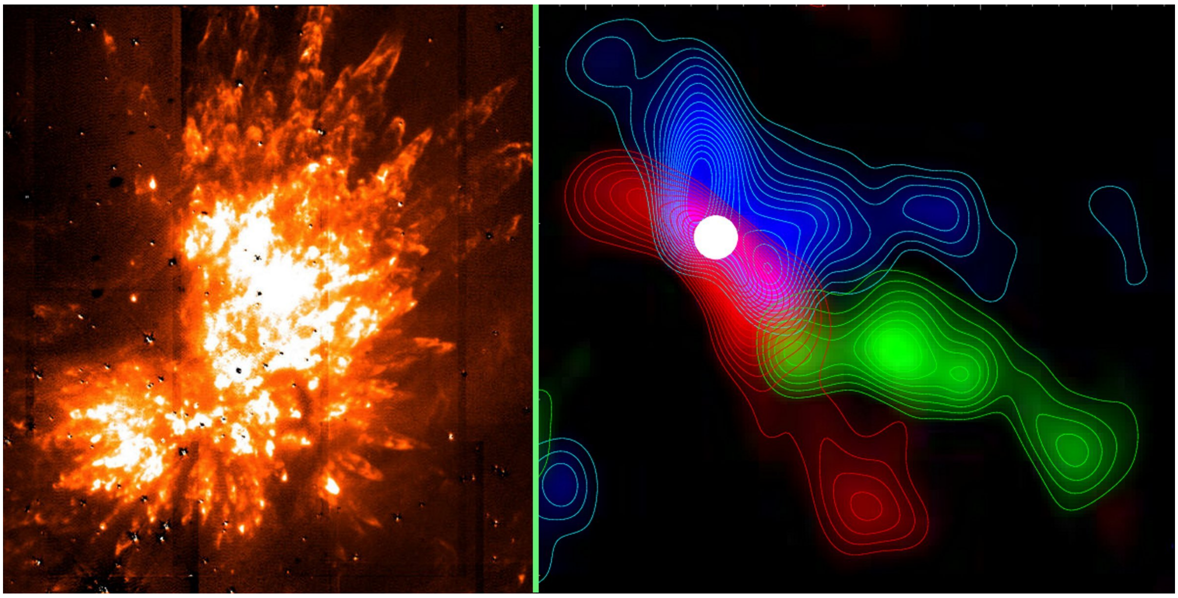

Figure 3: *Left panel*: Infrared nebula KL located in the Orion molecular cloud observed in IR Courtesy of Subaru (NAOJ). *Right panel*: ALMA integrated intensity color and contour maps of the SiO thermal emission The red wing represents redshifted gas with LSR velocities $15 < V_{LSR} < 25$ km s^{-1}, the blue wing represents blueshifted gas in the range $-15 < V_{LSR} < -5$ km s^{-1}. Courtesy of ALMA/NRAO/ESO/NAOJ.

suggestion was made that the debris ring is confined by shepherd planets, analogous to the confinement of Uranus's ϵ ring by the shepherd moons Cordelia and Ophelia. The results and the interpretation are shown in Fig. 2.

The nearest massive star forming region in our Galaxy is the Kleinmann-Low infrared nebula (KL, cf. Fig. 3), that is embedded in the Orion molecular cloud located behind the bright Orion gaseous nebula. It contains several obscure massive stars, detected at radio wavelengths by [16]. The most enigmatic of them is Source I. VLBI observations by [5] and [15] show strong water and vibrationally excited SiO masers concentrated very close to Source I, albeit with different distributions. The bulk of the emission at tens of AU scales surrounding Source I has an X-shaped geometry; the emission in the southeast is predominantly blueshifted, and emission in the northwest is predominantly redshifted. Zapata et al ([30]) used ALMA data to study the outflow arising from Source I at scales of thousands of AU. The observations of the thermal emission of the SiO 5-4 line at 217 GHz obtained during the CSV campaign achieved an angular resolution of $1''.8 \times 1''.2$. The large scale outflow has a butterfly-shaped morphology but, contrary to the emission close to Source I, the blueshifted emission corresponds to the moving gas found to the northwest and the redshifted emission is in the southeast (Fig. 3). SiO 8-7 emission at 345 GHz observed with the SMA by the same authors, with a resolution of $2''.9 \times 1''.9$ show a similar morphology and kinematical structure. Several possibilities to explain this phenomenon were discussed in [30] (two different bipolar outflows, ballistic ejecta from a rotating disk, change of the disk

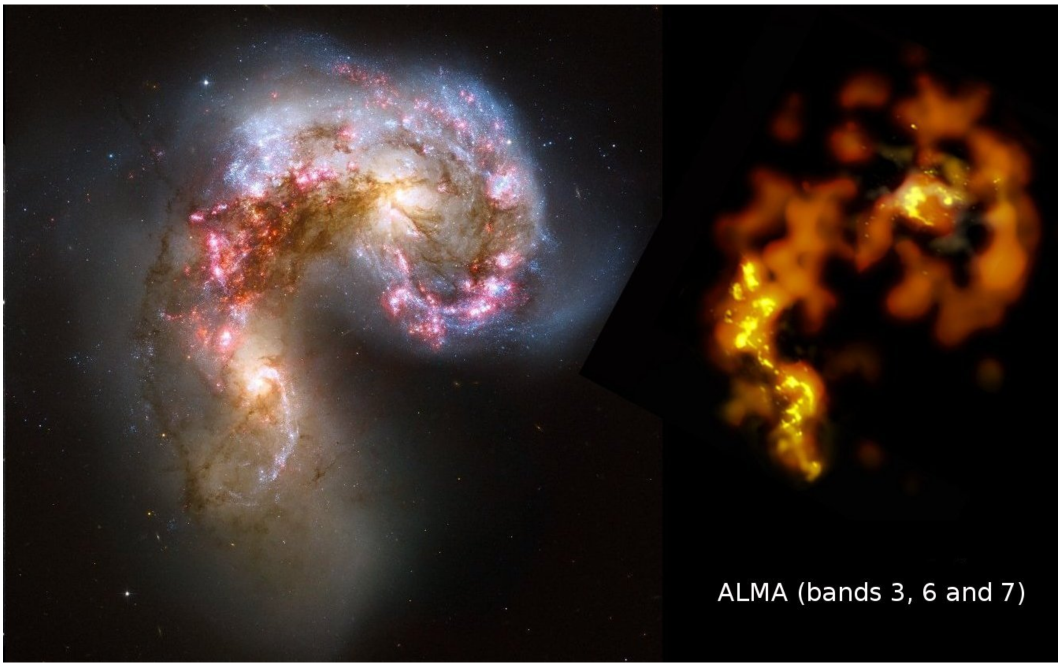

Figure 4: *Left panel*: HST ACS image of the merging pair NGC 4038/4039, also known as the Antennae or Arp 244. The overlap region is rich in gas and dust. Courtesy of STScI/NASA/ESA. *Right panel*: ALMA composite image of the molecular gas emission: CO 1-0 (orange), CO 2-1 (amber) and CO 3-2 (yellow). Courtesy of ALMA/NRAO/ESO/NAOJ.

rotation sense), with no clear conclusion. Observations at higher angular resolution, that can only be carried out with ALMA, are needed to discern at what spatial scale the outflow kinematics changes.

Almost half of the proposals approved for Cycle 0 correspond to extragalactic studies. This is not surprising, as the high sensitivity, high angular resolution, high image fidelity, and high mapping speed, together with a large frequency coverage, will make ALMA, once completed, the right instrument for high redshift studies, and for detailed dynamical and chemical studies of nearby galaxies, cf. [21]. A 'taste' of what the full ALMA will deliver in the future can already be obtained, even with a limited number of antennas.

The first paper published using ALMA data was a study of the Antennae overlap region by [6]. NGC4038/4039 is a nearby pair of colliding galaxies, a favorite target for studying how galaxy interactions affect the interstellar medium and star formation (Fig. 4). Previous studies (e.g. [29]) have revealed the large extent of the extranuclear region of star formation, which contains a large fraction of the molecular gas mass. The largest molecular complexes have masses of several 10^7 $M_\odot$, an order of magnitude larger than the largest structures seen in more quiescent galaxy discs. Most of the stars form in super-star clusters with stellar masses up to a few 10^6 $M_\odot$, as shown by [29] and [28]. During CSV the best submillimeter-wavelength image ever made of the Antennae galaxies was obtained observing three CO lines (Fig. 4). The study by [6] combined ALMA CO 3-2 and VLT/SINFONI H_2 1-0 S(1)

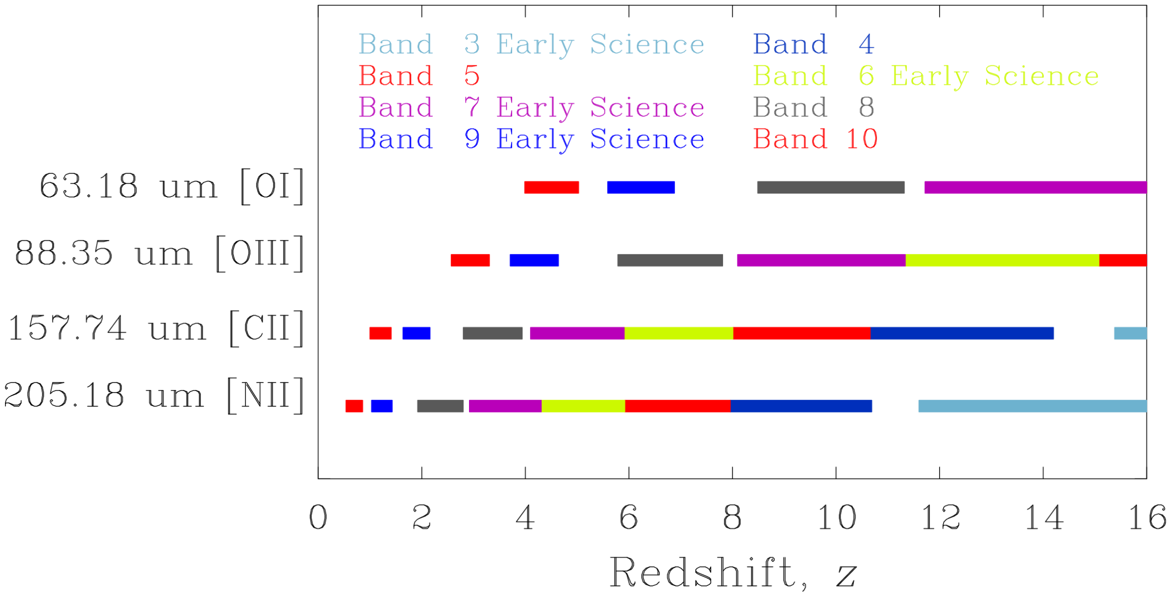

Figure 5: Redshift ranges (up to $z = 16$) for the observation of some atomic fine structure lines with the ALMA receivers currently installed or being build. Wavelength units are μm.

imaging spectroscopy at similar angular resolutions, $\sim 0''.8$, of the Antennae overlap region, where the super-giant molecular complexes (SGMC) lie. The ALMA high resolution and high sensitivity observations revealed several previously unknown details about the SGMCs. All but one have two spatially separated velocity components, offset from each other in velocity typically by 100 km s^{-1}. Given the sizes and masses involved, the authors conclude that the gas kinematics is likely driven by the galaxy interaction. The brightest source of H_2 emission is very compact, 50 pc in size and with a virial mass of a few 10^7 $M_\odot$, and coincides with the steepest CO velocity gradient in the region. The high H_2/CO ratio is exceptionally high, indicative of a high energy dissipation rate per unit mass with an estimated dissipation timescale as short as 1 Myr. Therefore, the compact source could represent an early stage of a super-star cluster in the making.

Some intense fine structure atomic lines (e.g. [NII] at 205.18 μm, [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 z is large enough (Fig. 5), e.g. the C^+ or [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, that arises primarily in photodissociation regions at the surfaces of molecular clouds, is the main coolant of the interstellar medium and may be better than CO lines to study the extreme redshifts, including the Epoch of Cosmic Reionization at $z > 6$ (ALMA bands 6, 4 and 3).

The [CII] 158 μm and thermal dust continuum emission of BR 1202-0725, a pair of gas-rich galaxies at $z = 4.69$, was observed with ALMA in band 7 during the science verification, in a 25 minute observation on-source. The BR 1202-0725 system consists of a luminous quasar host galaxy and a bright submillimeter galaxy (SMG) in likely interaction, although

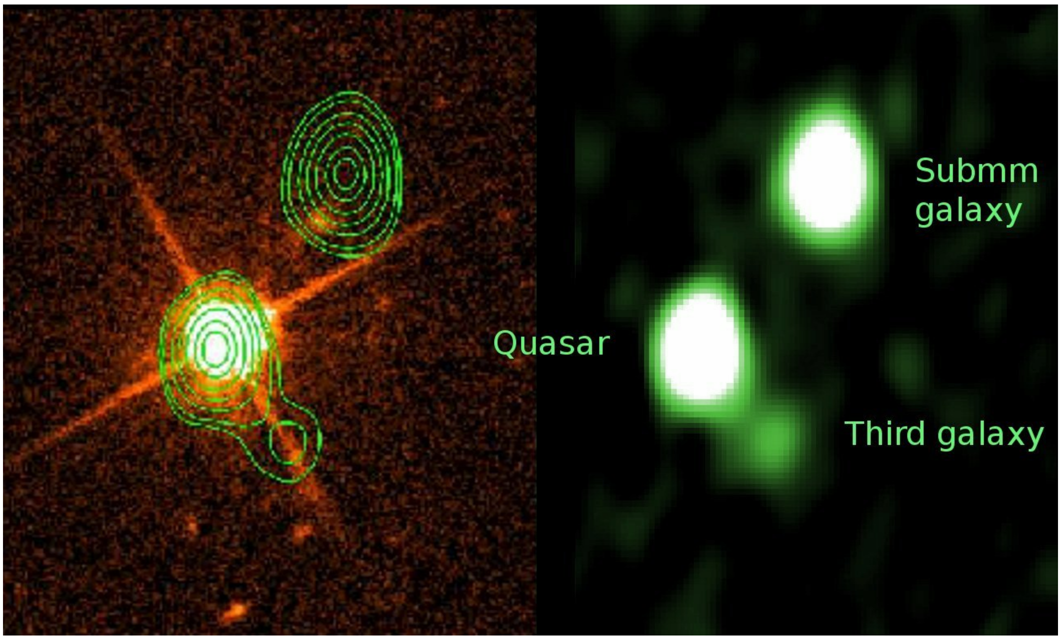

Figure 6: *Left panel*: Image of the object BR 1202-0725 obtained in the NIR by the HST at 0.775 micron. Contours show the 880 micron radio continuum emission detected by ALMA. *Right panel*: The radio continuum image obtained by ALMA at 880 micron clearly shows the quasar, the massive submillimeter galaxy associated with it and a third, faint galaxy. The synthesized beam size was $1.''30 \times 0.''86$. Courtesy of STScI/NASA/ESA and Jeff Wagg (ESO).

in a much earlier phase than the Antennae, the projected separation being 25 kpc. The [CII] luminosity computed by [27] is 10.0×10^9 $L_\odot$ for the SMG and 6.5×10^9 $L_\odot$ for the quasar host galaxy, less than 0.1% of their respective FIR luminosities, in agreement with what is found in ULIRGs and in other high-redshift galaxies (e.g. [26]). A third, ten times fainter star-forming galaxy was found next to the quasar in the 340 GHz continuum map by [27] (cf. Fig. 6). This galaxy was not detected with the SMA and the IRAM Plateau de Bure interferometers [19, 11, 24]. If the third galaxy lies at a redshift similar to BR 1202-0725, it would likely represent an extreme multiple merger event at high redshift, within 1.3 Gyr of the Big Bang, with a combined star formation rate of several 10^3 $M_\odot$ yr^{-1} [27, 24].

Approximately of the same cosmological age is the SMG LESS J033229.4-275619 observed with ALMA by [17]. Through ALMA cycle 0 observations, [17] have detected the [NII] 205 μm emission, that arises in HII regions. The much stronger [CII]158 μm emission had been previously detected with the SMA [4]. This is the only high-redshift object for with [NII] 205 μm and [CII] 158 μm detections are reported, what provides the first opportunity to assess the metallicity of high-redshift galaxies. The flux ratio [NII]/[CII] is 0.043 ([17]), similar to the ratios observed in the nearby universe, i.e. consistent with the solar metallicity, implying that the chemical evolution has progressed very rapidly in this system at $z = 4.76$.

4 Future scientific results

Three months after the SEA meeting took place, several additional papers with ALMA data had been published (e.g. [20, 9, 12, 23]). Scientists were receiving cycle 0 data, in some cases of higher sensitivity than expected due to the larger number of antennas in the array. Cycle 1 observations were planned to use an array of 32 or more antennas (more than 500 baselines) and this number will continue increasing till ALMA completion (50 antennas in the main array, 16 antennas in the ALMA Compact Array, cf. e.g. [7]). Single-dish and limited interferometer test observations with additional bands (4, 8 and 5) were being done prior to their future installation in the array.

ALMA is expected to make significant contributions in a variety of fields, providing images and spectra of a wide range of astronomical objects with great sensitivity (5650 m^2 main array collecting area), high angular resolution (down to $0\farcs015$) and very high spectral resolution ($R = 10^{4.9} - 10^{7.7}$), together with the large frequency range (84 to 950 GHz), high mapping speed (up to 1225 baselines), high image quality (image dynamic range up to $10^{4.7}$, spectral dynamic range up to $10^{4.0}$) and high fidelity (from degrees to $0\farcs1$ angular scales). The full ALMA will greatly exceed the performance of all existing instruments of its type. It may produce important discoveries during the Early Science campaigns, but experience with other large instruments shows that the epoch of higher productivity and greater impact usually starts a few years after its start-up, when the instrument has reached a stage of optimum performance and users have enough experience to bring it to its limits. Furthermore, as it is usually the case when a new instrument offers new capabilities to explore the Universe, we should expect that ALMA will surprise us with unexpected discoveries that will expand our knowledge.

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