DOI: 10.18727/0722-6691/5334

Ten Years of ALMA: Achievements and Future Perspectives

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This year marks the 10th anniversary of the inauguration of the Atacama Large Millimeter/submillimeter Array (ALMA), the world's largest radio observatory. Over the past decade, ALMA, an international collaboration in which ESO, representing its Member States, is the European partner, has revolutionised our view of the Universe from the Solar System to the most distant galaxies. ALMA has produced iconic images that have attracted worldwide attention, such as that of the planet-forming disc around the young star HL Tau, and contributed to the first image of the shadow of a black hole at the heart of the galaxy M87. In this article we look back at the main achievements of ALMA and provide an outlook into the future.

ALMA, a worldwide collaboration

In 2001 representatives from Europe, Japan and North America signed a Resolution affirming their intent to construct and operate a giant radio telescope in cooperation with the Republic of Chile. With this Resolution three previous top-priority astronomical large projects aimed at observations at millimetre/submillimetre wavelengths in Europe, Japan and the United States united behind one of the most ambitious projects in the history of astronomy: the Atacama Large Millimeter/Submillimeter Array[a] (ALMA).

The many superlatives of ALMA

ALMA has a long history of records as an astronomical facility, from its construction and operation at an unprecedented altitude of 5000 metres to the 6569 m^2 total surface area of its antennas, its capability to observe the Sun, the more than 200 Terabytes of data stored every year in its archive, and the size of its scientific community.

ALMA's construction started in 2003 on the Chajnantor plateau, at 5000 metres above sea level in the Atacama Desert in Northern Chile. The site was chosen for its altitude and dryness, providing the best conditions for scientific observations of millimetre and submillimetre waves, which are heavily absorbed by water vapour in Earth's atmosphere in lower-altitude, more humid, environments. This choice, however, came with strict requirements related to the construction, maintenance, and operation of the facility in such a harsh environment.

More than one thousand kilometres of optical fibre had to be installed for data transmission from the Array Operations Site (AOS) at 5000 metres altitude to the Operations Support Facility (OSF) just below 3000 metres. Two 20-metre-long transporters of 130 tons and 1400 horsepower each, Otto and Lore, had to be built to transport the 66 high-precision antennas of the ALMA interferometer from the OSF to the plateau. These transporters were also part of a novel operations concept in which the antennas are relocated within the plateau to enable a continuously expanding and contracting array with baselines from 15 metres to 16 kilometres, capable of producing images with resolutions better than 10 milliarcseconds. To generate such images ALMA's main correlator (Escoffier et al., 2007), equipped with 134 million processors, combines the signals arriving at the antennas and detected in one of the receiver bands between 0.32 and 8.5 millimetres (Tan et al., 2009) at any given time, a task requiring up to 16 quadrillion operations per second. Not surprisingly, the computing effort on the part of a globally distributed team to develop the software with which ALMA operates resulted in about 5.7 million lines of code at the end of construction in 2013.

But ALMA would not be the success that it has come to be without its community

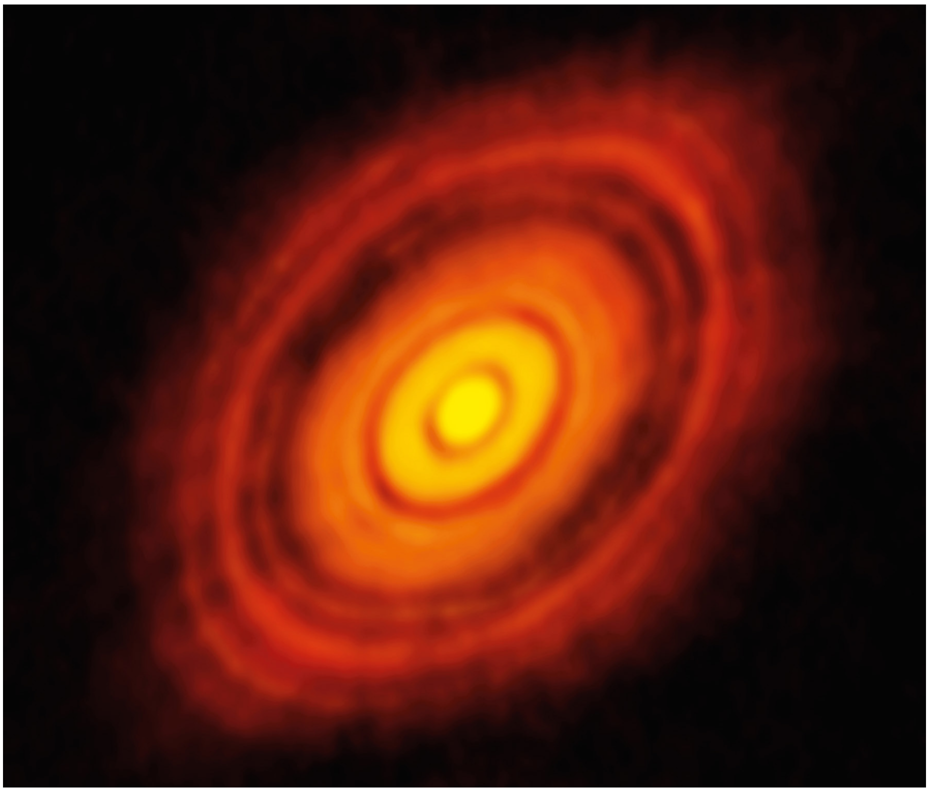
ALMA (ESO/NAOJ/NRAO)

Figure 1. This is the sharpest image ever taken by ALMA — sharper than is routinely achieved in visible light with the NASA/ESA Hubble Space Telescope. It shows the protoplanetary disc surrounding the young star HL Tauri. These new ALMA observations reveal substructures within the disc that have never been seen before and even show the possible positions of planets forming in the dark patches within the system.

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of more than 11 000 ALMA registered users. More than 4000 principal investigators and co-investigators request time to perform astronomical observations with ALMA following the yearly ALMA call for proposals and in 2022 alone nearly 9000 scientists from more than 50 countries worldwide published scientific results using ALMA data. This global community is the result of ALMA's investment in creating data reduction and calibration pipelines and providing high-quality data products through an archive rivalling those of space observatories (Stoehr et al., 2022), and in providing users with an extensive support network with the goal of making the facility accessible to all astronomers regardless of their radio-interferometry expertise (Zwaan et al., 2021). In Europe, the user support has been set up as an internationally distributed network of European ALMA Regional Centre (ARC) nodes (Andreani & Zwaan, 2006; Hatziminaoglou et al., 2015). This highly successful model has provided yet more means for ALMA to establish direct contact with the community and to widen its support across Europe and has inspired the European network of VLTI Expertise Centres, aimed at extending the community behind optical interferometry.

Figure 2. ALMA, located in the Chilean Atacama desert, is the most powerful telescope for observing the cool Universe — molecular gas and dust. ALMA studies the building blocks of stars, planetary systems, galaxies and life itself. By providing scientists with detailed images of stars and planets being born in gas clouds near our Solar System, and detecting distant galaxies forming at the edge of the observable Universe, which we see as they were roughly ten billion years ago, it allows astronomers to address some of the deepest questions of our cosmic origins. ALMA can also be used to study Solar System objects.

Scientific highlights

ALMA's scientific leadership is demonstrated by more than 3000 refereed publications since the start of operations. The original goals for ALMA[b] had sensitivity and high-resolution and high-fidelity images at their base. Indeed, ALMA's investment in pursuing such goals was key to major discoveries such as the image of the planet-forming disc around the young star HL Tauri (ALMA Partnership, 2015) or the first ever image of a black hole shadow in 2017 (Event Horizon Telescope Collaboration, 2019), featuring more than 1000 and 2000 citations, respectively, to date.

Beyond our galaxy, ALMA has excelled at detecting both normal and bright galaxies at increasingly large distances and mapping their dust and cold gas reservoirs in exquisite detail at the high angular resolution needed to image the interstellar

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Figure 3. A photograph of an Atacama Large Millimeter/submillimeter Array (ALMA) antenna at the ALMA Operations Support Facility (OSF). Part of the Milky Way can be seen in the night sky above the antenna.

medium (ISM) and resolve molecular clouds at cosmic noon, thus enabling the study of distant dust-obscured star formation (see Hodge & da Cunha, 2020 and references therein). The Large Programmes ALPINE and REBELS (Le Fèvre et al., 2020 and Bouwens et al., 2022, respectively) focus now on going all the way back to the epoch of reionisation, thus allowing a precise determination of the evolution of the cosmic molecular gas mass density since the early times. The future is bright in this area thanks to the large galaxy samples that will arise from facilities like JWST, Euclid, Vera C. Rubin Observatory and ESO's ELT, to name just a few; those galaxies will need to have their redshifts determined, confirmed or refined, and also their gas and dust resolved and characterised, ensuring that ALMA will remain a key player.

Complementary efforts to those linking the physical process that govern star formation to galaxy properties have been also made in our vicinity. Molecular clouds in the Milky Way have been mapped in different environments at high angular and spectral resolution to show the rich structure of filaments and cores that collapse gravitationally to form protostars and their interplay with the ISM (see, for example, the Large Programmes FAUST and IMF; Codella et al., 2021 and Motte et al., 2022, respectively). In particular, studies of the chemical complexity of protostars are also providing clues to the emergence of complex organic molecules in the ISM and are the target of the recently approved Large Programme COMPASS.

Zooming-in to already formed protostars and the discs around them, a major ALMA discovery was brought about by the high spatial resolution image of the dust in the protoplanetary disc around HL Tau, revealing gaps and rings that indicated that planet formation is well under way at stellar ages of ~ 1 Myr. The morphology of protoplanetary discs has now been extensively studied with numerous ALMA observations, including the DSHARP (Andrews et al., 2018) and MAPS (Öberg et al., 2021) Large Programmes. The distribution of dust and molecules in the discs is providing insights into the physical characteristics of the disc with, for example, temperature or density being traced with different molecules and their transitions. The disc images have also revealed velocity kinks and unveiled planets that could not have been discovered otherwise as they were occulted by dust.

Finally, ALMA has also carried out studies of the Sun and the Solar System, neutron stars, supernovae and transient events, to name just a few, demonstrating that ALMA's reach at ten years has already gone far beyond expectations and paving the way for new discoveries in the next decades.

ALMA in the 2030s

Looking to the future, ALMA has just begun the most powerful upgrade in its history, the Wideband Sensitivity Upgrade (WSU). This upgrade addresses the first priority of the ALMA 2030 development roadmap[1], a strategic plan for technical developments devised in consultation with the ALMA Science Advisory Committee and the scientific community and endorsed by the Astronet 2022–2035 roadmap[2].

The technical goals of the WSU are to broaden the system's bandwidth by at least a factor of two and up to four times the current value, and to upgrade the associated electronics and correlator. This will result in increases in ALMA's observing speed by at least a factor of three/six (for twice/four times the bandwidth) for observations at low spectral resolution and of up to a factor of 50 for spectral scans at high resolution, making ALMA even more powerful than it is today and setting the basis for more exciting discoveries in the next decades.

The first receiver band with wide bandwidth capability will be Band 2 (Yagoubov et al., 2020), covering the 67–116 GHz frequency range, for which the first receivers have just been successfully installed[3]. Band 2 completes ALMA's originally planned coverage of the atmospheric windows from 35 to 950 GHz and opens a new window at 67–84 GHz, enabling among other things the detection of complex organic molecules such as glycine, the characterisation of the fractionation of elements in our Solar System, evolved stars and young solar analogues, and the determination of completely new redshift ranges (Beltran et al., 2015; Fuller et al., 2016).

These goals are well aligned with the science drivers of ALMA 2030, arranged around the themes of origins of galaxies, origins of chemical complexity and origins of planets (Carpenter et al., 2022).

ALMA has detected gas in normal and bright galaxies across the history of the Universe, back to the time when the Universe was less than a billion years old, and it is now studying the structure and kinematics of such gas. Thanks to the wide bands afforded by the WSU and the improved sensitivity, the spectral scans needed to determine redshifts in unbiased galaxy surveys or to confirm photometrically determined redshifts will be 3.6 times faster than today. The gains in observing speed will be even higher for the high-spectral-resolution scans needed to advance further the study of the origins of chemical complexity across a vast range of astrophysical environments, enabling for instance comprehensive chemical inventories of filaments, cores and protostars in molecular clouds over all evolutionary states. Finally, building upon the revolutionary images of dust continuum in protoplanetary discs that reveal the presence of rings, gaps and spirals where planets are forming, the WSU will efficiently produce such images for a myriad of molecular lines. This will provide the means to advance towards a full understanding of the process of planet formation, since the gas contains most of the mass in protoplanetary discs and the morphology of different molecules can be used to determine the physical, chemical, and dynamical properties of the discs.

Concluding remarks

Ten years after its inauguration, ALMA has already transformed our understanding of the Universe, from the small to the largest scales. As the first of the 2020 decade's large facilities to become operational, ALMA has succeeded in having a scientific output comparable to those of other large facilities on the ground or in space, such as ESO's Very Large Telescope, ESA's XMM-Newton or the NASA/ESA Hubble Space Telescope at a similar age, while serving as a model for the operation and user support of future astronomical mega-facilities. Arguably, ALMA's most significant contribution to science may be that it was the first truly global astronomical facility. As outlined in the recent 2020 US Decadal Survey Report[4] "*Programmatically, the most dramatic development of the past decade has been the emergence of ALMA as a facility that engages the full (in terms of both wavelength and geography) astronomical community*". This is the best tribute to the dedication of all ALMA staff around the world who worked together to make ALMA happen. It is therefore time to celebrate: happy birthday ALMA!

Acknowledgements

M. Díaz Trigo thanks F. Stoehr for providing the statistics on the ALMA user community.

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Links

[1] ALMA 2030 development roadmap: https://almaobservatory.org/en/publications/the-alma-development-roadmap/
[2] ASTRONET 2022–2035 roadmap: https://www.astronet-eu.org/wp-content/uploads/2023/05/Astronet_RoadMap2022-2035_Interactive.pdf
[3] New ALMA receivers that will probe our cosmic origins successfully tested: https://www.eso.org/public/announcements/ann23013
[4] 2020 US Decadal Report: https://science.nasa.gov/astrophysics/decadal-2020/2020-decadal-survey

Notes

[a] ALMA is a partnership of ESO (representing its Member States), the National Science Foundation in the USA and the National Institutes of Natural Sciences in Japan, together with the National Research Council (Canada), the Ministry of Science and Technology and the Academia Sinica Institute of Astronomy and Astrophysics (Taiwan) and the Korea Astronomy and Space Science Institute (Republic of Korea), in cooperation with the Republic of Chile.
[b] ALMA's original goals were:
- 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 disc at a distance of 150 pc, enabling one to study the physical, chemical, and magnetic field structure of the disc and to detect the tidal gaps created by planets undergoing formation; and
- the ability to provide precise images at an angular resolution of 0.1 arcseconds.