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ALMA at Ten Years: Past, Present and Future

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In December 2012 the first results from Early Science observations by the ALMA Observatory were discussed at a workshop held in Puerto Varas, Chile. In 2013 ALMA was inaugurated and only ten years later it has revolutionised our view of the Universe, both near and far. In December 2023 the scientific community returned to Puerto Varas to attend the conference ALMA at ten years: Past, Present and Future, celebrating ten years of ALMA operations. In this article, we report on the outcome of this conference.

Introduction

The conference was structured around five main scientific categories, from the high-redshift Universe to the Solar System and the Sun. In addition, observatory-specific topics were presented, from ALMA's history and current status to technical developments in the near and far future. The conference included in-person and online talks. Posters were displayed online and at the conference venue and highlighted in poster-flash sessions interleaved with the oral contributions throughout the conference.

An important goal of the conference was to showcase the success of ALMA, both in terms of its scientific reach and its diverse community. This was amply achieved with an attendance of more than 300 participants, of whom nearly 55% attended in person (Figure 1). Figure 2 shows the distribution of participants by career stage, region and science category. The ALMA reach is reflected in all and each one of such distributions, from the more than 20% of Chilean participants to the nearly 50% of young astronomers and the multiple science topics. ALMA is clearly attracting astronomers from a wide range of areas, well beyond traditional areas of millimetre/submillimetre astronomy and it keeps on renewing its community with young astronomers.

Scientific highlights

High-redshift galaxies

ALMA has opened the study of the interstellar medium (ISM) in high-redshift galaxies thanks to increased sensitivity, better angular resolution, access to submillimetre bands (> 300 GHz) and new observing modes, such as frequency scans, compared to previous facilities. ALMA has detected and imaged emission from a galaxy at z = 9.119 (Hashimoto et al., 2018), but more importantly it has

Figure 1. In-person participants.

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increased the sample from ~ 200 galaxies known at $z > 1$ before ALMA to thousands now, with a significant fraction above $z > 4$ found by the Large Programmes[1] (LPs) ALPINE and REBELS.

High angular resolution has enabled the discovery of dense, highly star-forming protocluster systems at $z > 3$. The break-up of previously known submillimetre galaxies in multiple galaxies also showed that many of them were main-sequence galaxies rather than starburst ones. ALMA has also imaged the kinematics of discs at high redshifts, showing that rotation-dominated discs are already present at early times, in contrast to previous trends observed in warm gas (Hα) and simulations, which indicated clumpy, thick discs, dominated by turbulence. Using [CII] and dust in addition to CO, the field is further progressing by performing a census of stars, gas and dust for main sequence galaxies at $z \sim 4$–6 at 1–2.5 kpc resolution (for example, with the LP CRISTAL).

Another significant achievement of ALMA has been to demonstrate that the star formation rate density in the Universe is driven by gas mass rather than by star formation efficiency at $z \sim 1$-4. While a significant number of obscured star-forming galaxies have been unveiled at $z \sim 4$–7, demonstrating that the Universe was already dusty at < 1 Gyr of age, efforts are now ongoing to find the first massive quiescent galaxies at such redshifts and thus shed light on the question of why galaxies quench star formation. Importantly, many of the results in this field have not yet pushed ALMA to the highest angular resolutions or frequencies, and advances are already foreseen, for example by using the highest frequencies to constrain dust masses and temperatures.

Nearby galaxies and galactic nuclei

In more nearby galaxies, ALMA is being exploited to investigate star formation over cosmic time (LP PHANGS) or the origin and role of feedback in galaxy evolution.

Observations of galaxy bars at 0.5-parsec resolution show super star clusters hosting more than 1000 O-type stars. In these clusters, spherical outflows are found to be expelling a large fraction of molecular gas that may have an origin in winds from the O-type stars and/or dust-reprocessed radiation pressure. Feedback from outflows of active galactic nuclei (AGN) at the core of galaxies is also being searched for, although so far no clear depletion or enhancement of the molecular gas content of galaxies with AGN and the control samples of pure star-forming galaxies has been found.

As part of the Event Horizon Telescope, ALMA provided the crucial sensitivity needed to obtain the first image of a black hole via very long baseline interferometry (Event Horizon Telescope Collaboration, 2019). The image shows the shadow of the supermassive black hole at the centre of the galaxy Messier 87 (M87) and obtained more than 4.5 billion image views shortly after being released!

ALMA's sensitivity can probe how these supermassive black holes are fed by stars, by monitoring the nonthermal emission from the so-called tidal disruption events that result from such feeding, and investigate the potential role of black hole spin to form jets in these events. ALMA's exquisite angular resolution has been used to identify the host galaxies of other transient events such as gamma-ray bursts or fast radio bursts and to characterise their environment, indicating, for example, that the latter can arise in a wide range of environments, from star-forming regions to old populations within a galaxy.

Star formation and the ISM

Following the discovery of the prebiotic molecule glycolaldehyde towards a solar-type star with ALMA Early Science Verification data, astrochemistry has become a key scientific tool of the ALMA community, especially but not only in the fields of star formation and the ISM. More than 100 different species were identified towards a protostar in just one programme (PILS; Jørgensen et al., 2016) and studies are now attempting to establish how the environment impacts chemistry, including not only protostars but also comets (LP COMPASS). The earlier stages of star formation, such as core collapse, are being investigated via deuterated species that can trace the densest gas, and the core mass function of young massive protoclusters has been revealed as top-heavy by the LP ALMA-IMF, which has also found a correlation between the power-law index of the core mass function high-mass end and the cloud properties and evolutionary stage.

The access to diverse spatial scales has also allowed the characterisation of as many as a thousand clumps by the LP ALMAGAL and the ability to follow individual stars as they form in our own Milky Way, including the discovery of protostellar multiplicity requiring disc and turbulent fragmentation.

Polarisation observations have further looked at which stage discs form around protostars and the role of magnetic fields in such formation, seeming to indicate that external irradiation by cosmic rays is not sufficient to ionise the gas so that it can couple to the magnetic field that is thought to regulate disc formation via extraction of angular momentum.

Finally, ALMA is also looking at the diffuse ISM in absorption to find the earliest stages of molecule formation, and has already revealed puzzlingly high abundances of SiO in low-density, non-star-forming diffuse gas and shown that photodissociation regions cannot explain the high HCO+ column densities observed in directions in which HI has a temperature higher than 40 K and non-equilibrium chemistry may be required.

Circumstellar discs

ALMA revolutionised the study of circumstellar discs with its iconic image of the protoplanetary disc around the young star HL Tau, where the network of rings in the disc demonstrates that planet formation is under way at stellar ages of 1 Myr (ALMA Partnership, 2015). Current studies are moving towards characterising precisely the moment at which rings appear by imaging protoplanetary discs around protostars at even younger ages and characterising such discs via detailed maps of dust and gas, the latter being enabled by the detection of numerous molecules that trace different densities,

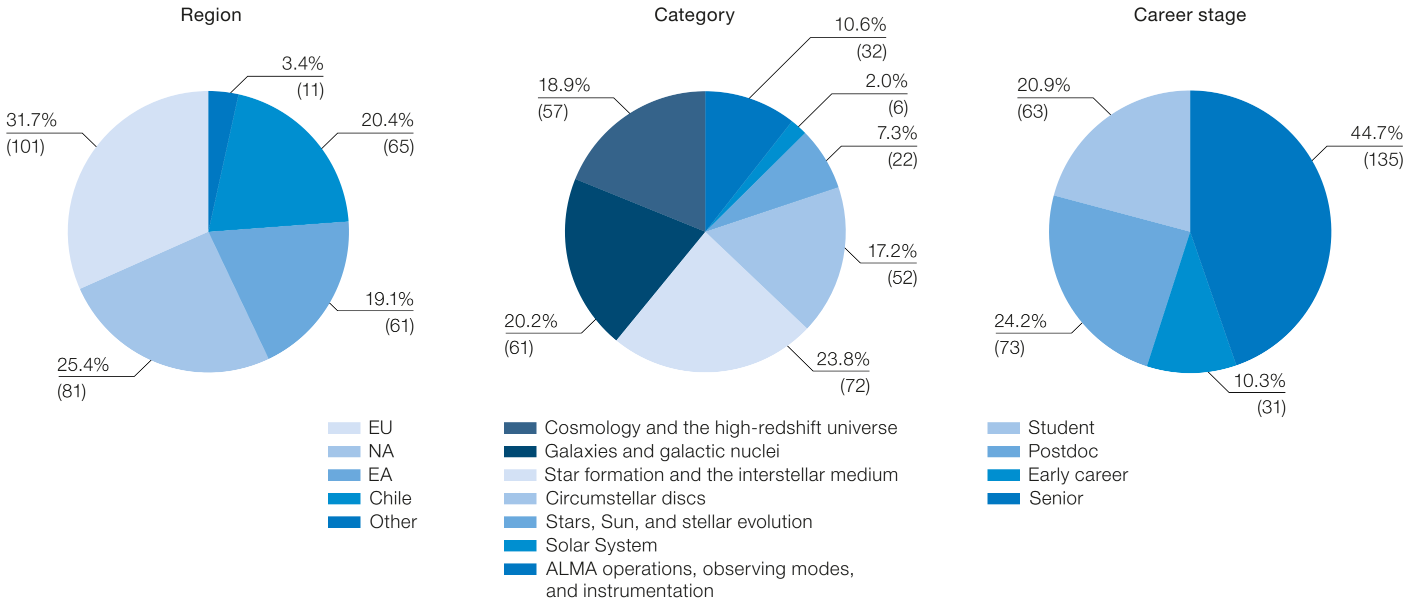

Figure 2. Demographic distributions of the conference participants by geographical region, scientific category and career stage of conference participants.

temperatures and environments (for example the LP MAPS).

An important new aspect of these studies is how the chemistry in discs is affected by X-ray flares from the protostar, thus bringing protoplanetary studies into the realm of time-domain astronomy. A significant advance has also been provided by precision kinematic studies that have detected distortions in the velocity structure in discs that suggest the presence of embedded planets (LP exoALMA). Finally, polarisation observations are exploring the importance of magnetic fields in the alignment of dust grains. Observers in this field, however, have emphasised the need for long (including LPs) multi-wavelength observations to disentangle the effect of magnetic fields from that of self-scattering in aligning the grains.

Closely related to these studies are those of debris discs. ALMA's resolution and sensitivity have revealed that belts are morphologically diverse, and have radial and vertical substructures possibly caused by planets, and cold gas with an uncertain origin, either exocometary or remnants from the protoplanetary phase (for example the LP ARKS).

Stars and stellar evolution

In the field of evolved stars, ALMA has been key in demonstrating that stellar winds have 3D inhomogeneities that were much more pronounced than ever thought. ALMA has seen the impact of a binary companion shaping the winds at thousands of stellar radii, indicating that mass loss rates have been long overestimated by being based on single-star evolution models. Observations are also now being pushed to the limits of angular resolution (as far as 8 milliarcseconds for observations of the red supergiant Betelgeuse!) to study the distribution of molecular gas and dust down to the stellar atmosphere, based on which the presence of convective cells in the photosphere has been already revealed in an asymptotic giant branch star (Velilla-Prieto et al., 2023). But ALMA has also investigated how dust forms from oxydes and hydroxides (LP ATOMIUM), thus indirectly providing information about what is happening at scales as small as nanometres.

Further down the path of stellar evolution, ALMA is now providing new insights into explosive events related to stellar death, such as supernovae and the remnants of those explosions. Explosive events involve blast waves, which expand in the circumstellar medium and beyond, creating shocks. The evolution of the synchrotron emission at millimetre/submillimetre wavelengths provides information about the properties of the ejecta and the surrounding medium and allows a unique look at the earliest times since the millimetre/submillimetre emission peaks before emission at longer wavelengths.

Surprises are also arising in the study of remnants such as rotating neutron stars or pulsars. While pulsars have a very steep spectrum at radio frequencies and were therefore not expected to show significant emission in the ALMA bands, the phased-mode of ALMA has already enabled it to detect an emission component at 100 GHz in the Vela pulsar, distinct from the component peaking at 1.4 GHz. Further community efforts are now being targeted on the search for pulsars at the Galactic centre, which would enable high-precision tests of strong gravity around the supermassive black hole at the centre, Sgr A* (Torne et al., 2023).

The Solar System and the Sun

Closest to home, ALMA has also opened a new discovery space in the area of planets and their moons or comets, as spacecrafts are not typically equipped with millimetre–wavelength instruments. ALMA has mapped the chemistry, derived the temperature structure and studied the kinematics of atmospheres, mapped zonal winds and identified volcanoes in planets and their moons. ALMA has also been highly synergetic with space missions in the Solar System, for example by observing nitriles in Saturn's moon Titan and complementing the hydrocarbon measurements from Cassini's flyby. Remarkably, some of the results have been derived from the use of Titan as a calibrator for other ALMA observations, highlighting that new species can be detected in only a few minutes of observations. In comets, ALMA has allowed for the first time tracing molecular species to the coma, helping to link interstellar and planetary ice and gas reservoirs (see also LP COMA).

Finally, ALMA has observed the Sun at various frequencies that are sensitive to different levels of the chromosphere, allowing a map to be built of its temperature structure and making progress towards answering the fundamental question of how the chromosphere is heated. As Stephen White said in his talk, *"ALMA solar observations provide tests that establish the physics needed to understand the solar atmosphere and by extension the atmospheres of all stars."*

ALMA development

The ALMA Programme Scientists gave an overview of the development projects and studies that are taking place at the ALMA regions. Such development is the key pillar of the Wideband Sensitivity Upgrade (WSU), presented by the Observatory Scientist. ALMA will rejuvenate as it approaches 20 years of operations by undergoing an upgrade of the full signal chain, from the receivers and digitisers, all the way to the correlator, which will result in increases in sensitivity for all observations. This is fundamental to taking advantage of the planned upgrade of the receivers to increase their instantaneous spectral bandwidth by as much as a factor of four. Observations at full spectral resolution over the entire bandwidth will result in increases of the spectral scan speed of up to a factor of 50 for the highest spectral resolution, and make ALMA an even more powerful tool to explore the Universe. Discussions in this session touched on how to best access and prepare for data analysis and exploitation of the massive sets that will be obtained. Beyond the WSU, former ALMA Director Pierre Cox encouraged the scientific community to start thinking about the key scientific questions of the 2040s and the relevant capabilities that ALMA needs to solve them.

Outlook

ALMA has opened a new window onto the millimetre Universe and revolutionised our understanding in areas as diverse as the high-redshift Universe and star and planet formation. However, the conference has made clear that ALMA's capabilities have not yet been fully exploited. For example, high-frequency observations are necessary to unequivocally determine the dust temperature or to measure far-infrared probes of gas and dust at the peak of cosmic star formation. Further, a combination of capabilities such as multi-wavelength polarisation and high angular resolution are 'a must' for advancement, as demonstrated by the maps of the protoplanetary disc around HL Tau with ALMA (Stephens et al., 2023) or the supermassive black holes M87* and Sgr A* with the EHT (Event Horizon Telescope Collaboration, 2024) that are required to disentangle the signatures of magnetic fields and scattering.

ALMA is now embarking on an upgrade that will further broaden the receiver bandwidth, increase the sensitivity, and deploy a vastly more powerful correlator, enabling wideband scans at high spectral resolution. Further advances are therefore expected in all fields in the next decade. With a steadily increasing community and the ongoing upgrades, the future is bright for ALMA.

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Links

[1] ALMA Large Programs: https://almascience.org/alma-data/lp