Report on the Conference

The First Year of ALMA Science

held at Puerto Varas, Chile , 12–15 December 2012

Leonardo Testi[1]
Paola Andreani[1]

[1] ESO

The conference reviewed the scientific results of the first year of ALMA Early Science operations and a summary of the highlights is presented. All areas of ALMA Cycle 0 science were covered, with emphasis on new results for astrochemistry, the Solar System, star and planet formation, the life cycle of stars, nearby galaxies, active galactic nuclei and the high redshift Universe. The priorities and prospects for ALMA Full Science and ALMA upgrades were also discussed.

Figure 1. The participants at the First Year of ALMA Science conference held in Puerto Varas, Chile.

ALMA Early Science Operations Cycle 0 observations started on 30 September 2011. Before then, in spring and summer 2011, the observatory had started to release science-qualified Science Verification (SV) datasets. The first scientific papers based on ALMA data started to appear in press at the beginning of 2012. Since the Cycle 0 observation season was completed at the beginning of 2013 (see Zwaan et al. p. 20), December 2012 was perfect timing to review the first ALMA science results in a dedicated conference.

The conference was co-organised and co-sponsored by all the ALMA partners, with an important additional contribution from the European Commission FP7 Radionet-3 project. 199 astronomers from all over the world gathered in the beautiful setting of the town of Puerto Varas in southern Chile to discuss ALMA science (see Figure 1). Senior astronomers and many young students and postdocs shared their enthusiasm over the first ALMA results. Thijs de Graauw, Massimo Tarenghi and Pierre Cox, current, previous and future ALMA Directors respectively, addressed the participants, sharing with them their insights and reflections on the initial phases of construction, the excitement of delivering the first science observations and the great expectations for future science results. Two public evenings were also organised as part of the conference events, with Raphael Bachiller (Director of the Observatorio Astronómico Nacional [OAN] in Madrid, ESO Council Member and Chairman of the Radionet-3 Board) and Juan Cortes of the Joint ALMA Observatory (JAO) presenting the ALMA project and its science objectives to the general public.

The promise of ALMA was to revolutionise many scientific areas by providing an unprecedented quantity and quality of high spatial and spectral resolution (sub) millimetre wavelength spectral line data. The ALMA challenge is then to allow observers to perform detailed tests of astrochemical models, star and planet formation, galaxy formation and evolution, and many other investigations. Throughout the conference, the transformational power of ALMA data, even with the limited capabilities available so far during SV and Cycle 0, were emphasised many times. The enormous progress in sensitivity and image fidelity provided by ALMA, even at these early stages, was clearly demonstrated.

The science programme for the conference included eight overview talks introducing the different areas of ALMA science, 43 oral contributions, all presenting results from ALMA data, and approximately 100 posters on observational, theoretical and instrumental topics connected with ALMA. Below we provide a short summary of the main science highlights; the programme is available on the conference web page[1].

Astrochemistry

Astrochemistry was one of the main recurring topics in the conference, across all the science areas. ALMA's sensitivity has transformed the field of astrochemistry from the confines of exotic Galactic sources and a few starburst galaxies to a theme that encompasses all areas of ALMA science. Different chemical evolutionary paths during the formation of protostars were discussed at the conference: the new ALMA data are highlighting not only the distinction between "hot corino" and "warm carbon chain chemistry" protostars, which need to be understood and reconciled in a common framework, but also the chemical complexity of the interplay between dust, ices and different molecular species and isotopologues in the path from clouds to planetary systems.

The chemistry of deuterated and complex organic molecules in protostars and discs

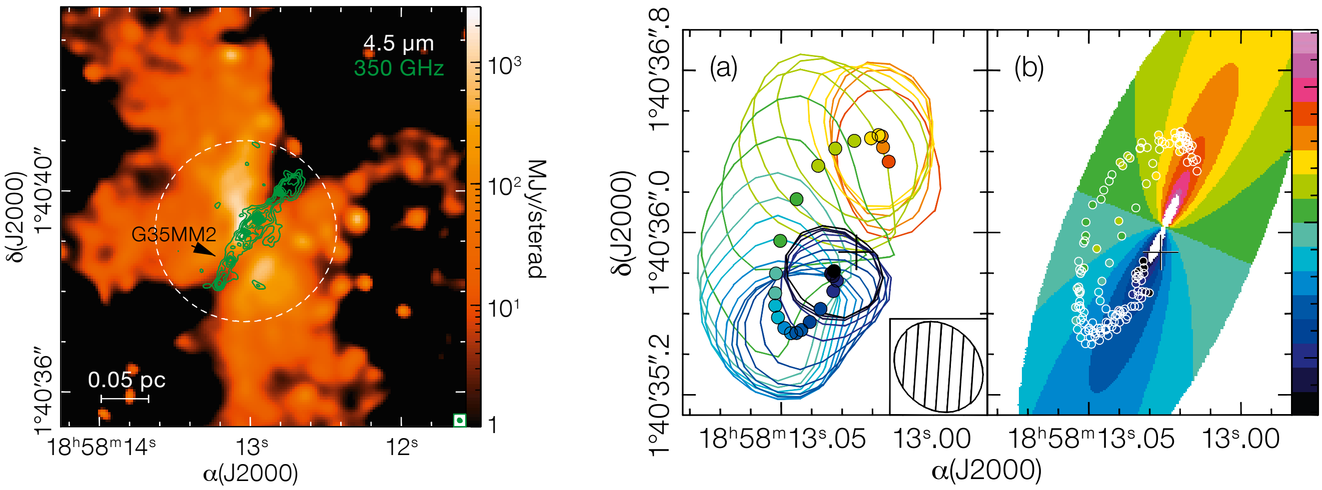

Figure 2. The candidate Keplerian disc around a massive (proto-)stellar system in G35.20-0.74N. In the left panel, the ALMA 350 GHz continuum emission (green contours) is overlaid on the 4.5 µm Spitzer image. The right panels show the kinematical analysis of the disc. To the left is shown the result of the kinematical analysis of the molecular line data towards the hot core (B) in this region with the small filled circles showing the displacement of the photocentre in various velocity channels and the coloured contours showing the full width at half maximum of the emission in each of the velocity channels. To the right is shown the comparison to a disc with a Keplerian velocity pattern. ALMA resolves the emission from several components of the (19-18) transition of methyl cyanide (CH_3CN), as well as transitions of vibrationally excited methanol (CH_3OH) and the HC_3N molecule, both spatially and kinematically, at sub-arcsecond resolution. These complex organic molecules trace the inner few thousand astronomical units of a disc that is well modelled by the Keplerian rotation pattern orbiting a central mass of 18 $M_{\odot}$. Figure adapted from Sánchez-Monge et al. (2013), in press.

was a major discussion topic, with talks and posters showing the mapping of water isotopes and deuterated species in the planet-forming regions of discs. In a young solar analogue a simple sugar, glycolaldehyde, has been detected (see Release eso1234), which is thought to be an essential step in developing biotic molecules, in particular the RNA molecule. The impact of astrochemistry on extragalactic studies was also highlighted by the Cycle 0 observations of nearby and high-redshift galaxies, which at the ALMA sensitivity are now showing emission from many of the complex and less abundant molecules that have, so far, been mostly studied in our own Galactic environment.

Solar System science

The power of ALMA to study and understand the atmospheres and surfaces of bodies in our own Solar System was reviewed. Some of the main topics where ALMA is expected to make a contribution are in the characterisation of the chemical composition and seasonal variation of the atmospheres of planets and moons, and preliminary ALMA maps of Venus and Titan illustrated this point. A detailed analysis of a combined Herschel–ALMA study of the great storm in Saturn's atmosphere was also presented. The analysis of the data from the two observatories confirms that, while the differing CO intensity inside and outside the storm is just caused by a higher temperature within the storm and not by an abundance variation, the H_2O abundance in the storm is higher than in the rest of the stratosphere of the planet and was probably caused by the vapourisation of icy clouds and enrichment with material from the O-rich troposphere. Much progress is expected to come from the study of the chemical composition of comets, which should provide important constraints on the origin of water and, possibly, complex organic molecules on Earth.

Star formation

Besides the chemical studies, ALMA is now providing new insights on the physical and kinematical structure of protostars and young stellar objects. The first hints that ALMA has started to address directly the long-standing problem of the kinematical signature of disc formation during protostellar collapse was presented at the meeting. Detailed analysis of the CO isotopes in Class 0 protostars reveals a possible break in the kinematics of the collapsing envelope within the central 30–40 AU, an indication of a small inner disc in Keplerian rotation around the central protostar.

The quest for the initial conditions for high-mass star formation has already been brought to a new level with ALMA, where detailed studies of different candidates across the Galaxy provide critical data that can now be directly compared with numerical models. The role of discs and outflows and their structure in the formation of highest-mass stars was also addressed. Tantalising new evidence for Keplerian discs surrounding very massive protostellar candidates provides direct constraints on the formation mechanism (see Figure 2 for an example). The high angular resolution, sensitivity and wide-area interferometric mapping capabilities of ALMA are also proving to be a key tool to understand the formation of very massive clusters, both in our Galaxy and in the Local Universe. The spectacular images of a proto young massive-cluster candidate near the Galactic Centre reveal for the first time a chemical, physical and kinematical complexity that will keep both observers and theorists occupied for several years.

Planet formation

Several new ALMA Cycle 0 results were presented on the structure and evolution of protoplanetary discs and the implications for the formation of planetary systems. Observations of dust evolution in discs around very low-mass stars and brown dwarfs with ALMA cannot easily be explained with the existing dust evolution models, suggesting that our understanding of the processes governing dust evolution in discs is not complete (see Release eso1248). The detection of CO in several of these discs around young brown dwarfs confirms that some of these are indeed surrounded by relatively large and massive discs.

Even in Cycle 0, ALMA has already started to transform the field of planet formation. The sensitivity of ALMA in the high frequency bands, as compared to the previous facilities, has allowed high quality images to be obtained of the asymmetries in the dust distribution and quantitative measurement of the gas content in the inner dust-evacuated holes of evolved discs. The data reveal indirectly the presence of forming planets and constrain the flow of material from the outer disc through the planet and into the inner regions of the system (see Figure 3 and Release eso1301). The dust asymmetries are interpreted as the effect of a planet that induces an asymmetric pressure variation in the outer disc, creating an efficient trap for dust grains. The ALMA sensitivity and angular resolution also allows the direct detection of the CO-emitting layer in the large disc around HD 163296 and to directly constrain the flaring of the disc in molecular gas.

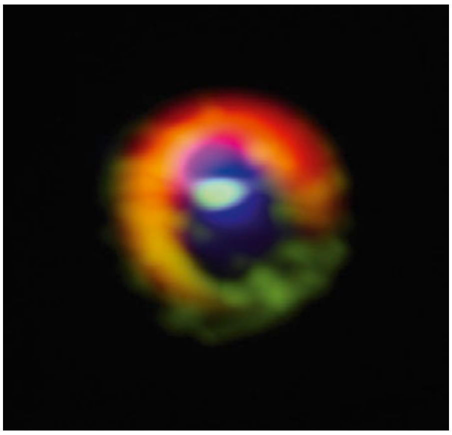

Figure 3. The disc around the young star HD 142527 shown in a montage of HCO^+(4-3) and CO(3-2) emission and dust continuum, highlighting the streams of gas flowing across the gap in the disc. The dust emission in the outer disc is shown in red, dense gas in the streams flowing across the gap, as well as in the outer disc, is shown in green (HCO^+ emission), and diffuse gas in the central gap in blue (CO). The gas filaments can be seen at the three o'clock and ten o'clock positions. From Casassus et al. 2013; see Release eso1301 for more details.

Stellar evolution

ALMA can also provide new constraints, not only on the cool side of the Universe, but also on the hot atmospheres of stars. Multi-wavelength observations at centimetre and millimetre wavelengths of the stellar chromospheres can allow the amount of magnetic heating in stars to be probed. For this reason, its capability to observe the Sun is one of the key features of ALMA, and has been designed into the system from the very beginning of the project. While observations of the Sun are still being tested and commissioned, ALMA has been observing different phases of stellar evolution from the beginning of Cycle 0. Millimetre flares in young stellar objects have been recently observed and will become an important topic for ALMA science owing to the high sensitivity available.

Millimetre continuum observations will also be critical to separate the non-thermal emission from the coronae and the stellar wind components, allowing direct measurements of the mass loss in stars of various masses and ages. Initial results in this area are expected from Cycle 1 programmes. In Cycle 0, several programmes focused on the study of the mass loss in the late stages of evolved stars. Observations of stars in the late stages of stellar evolution provide constraints on the chemical enrichment of the interstellar medium. Some of the most spectacular ALMA data on the late stages of stellar evolution presented at the meeting included: the mass-loss history following the thermal pulse in the asymptotic giant branch star RScl (see ESO release eso1239 and the cover of *The Messenger* 149) and detection of the dust, CO and SiO emission in the ejecta of SN 1987A in the Large Magellanic Cloud.

Galaxy formation

In the nearby Universe there is the potential for ALMA to directly study the sites of star formation, i.e. giant molecular clouds (GMCs), in order to derive the star formation efficiency and the gas depletion time on sub-galactic scales. These can be related to galaxy properties, such as metallicity, cloud densities and pressures, and velocity dispersions. Some nearby galaxies have already been targets of ALMA SV projects. The impressive M100 large-scale mosaic shows that CO emission traces a two-armed spiral and a double bar out to 10 kpc and that the time needed for the current star formation rate to consume the existing gas reservoir is 1.7–1.9 Gyr.

Molecular gas fragmentation has been observed to occur at parsec (pc) scales along filamentary structures in NGC 253, the Antennae Galaxy and 30 Doradus. At galactic scales, the parents of these filamentary structures are GMCs, with masses of ~ 10^{5-6} $M_{\odot}$ and sizes of tens of pc. These are found in spiral galaxies and in the interarm region of the overlap of the arms of the Antennae. A newly discovered tidal filamentary arm was presented in NGC 4039, 3.4 kpc long and < 200 pc wide, where the star formation efficiency is a factor of ten larger than in disc galaxies.

ALMA's resolution also enables details of the centres of nearby mergers to be probed. Double nuclei have been detected in NGC 3256, similar to those in Arp 220, while in NGC 34 (a luminous infrared galaxy with an active galactic nucleus [AGN]) Band 9 CO(6–5) observations are consistent with two nuclei: one associated with a starburst and another with the AGN.

Several presentations clearly pointed out the fundamental contribution that ALMA is providing to the field of galaxy formation in addressing the major mechanisms: merger and starburst-driven or governed by secular evolution. An initial attempt to answer some specific questions was carried out by the LESS and COSMOS continuum surveys with the determination of galaxy counts. These surveys also enable better estimation of the spectral energy distribution (SED) of galaxies, and therefore of the dust mass and gas fraction.

Active galactic nuclei

One of the biggest puzzles in active galactic nuclei physics is the removal of the angular momentum from the disc gas and mechanisms driving infall down to the nucleus on scales of tens of parsecs. Simulations suggest a role for galaxy bars, but no correlation between AGN activity and bars is seen. New ALMA results for two sources (NGC 1433 and NGC 1566) show that the dense molecular gas seems to fall into the nucleus at the unprecedented spatial resolution of 24 pc. The kinematics of the nuclear spiral arms in NGC 1097 have been followed down to ~ 50 pc from the central supermassive black hole (SMBH) from the ALMA detection of HCN, a tracer of high density gas.

Absorption lines in the spectra of AGN, the nearby Centaurus-A (Cen-A) and PKS1830-211 at $z = 0.886$, were also shown. Such investigations offer a unique opportunity to find gas that might be feeding the AGN. Towards the SMBH of Cen-A, the gas becomes denser, warmer and influenced by the presence of photon dissociation regions (PDRs). Detailed study of absorption lines towards AGN reveals the chemical enrichment of the Universe through isotopic ratios and can constrain the constancy of fundamental constants by detecting line shifts with respect to laboratory measurements, such as in PKS1830-211, where ALMA observations include water in absorption.

Molecular outflows may be associated with AGN activity or with vigorous starbursts and have been detected with ALMA in HCO^+(4-3) and CO(3-2) through their high-velocity wings. In the centre of NGC 253, the ALMA detection of the H40α line in a molecular outflow raises the question of the mechanism for efficient transfer of angular momentum to the molecular gas. Several talks pointed out the need to measure outflow rates of cold gas and test star formation and AGN feedback models. A key issue is the investigation of the processes that quench star formation and turn galaxies into "red and dead". New ALMA results were presented on a sample of extremely rare ultra/hyper-luminous very red radio-loud quasars, which are considered young jet feedback candidates at $z = 0.5$–3. ALMA is able to put strong constraints on the presence of cool dust and star formation, and to confirm that this sample consists of heavily obscured Type 2 quasars, often Compton-thick and very strongly AGN-dominated; some sources do not show any evidence of star formation.

The environment around galaxies, such as the X-ray cavities in galaxy clusters provides good locations for measuring the mechanical power injected by the SMBH. AGN heating is energetically sufficient to offset radiative cooling in galaxy cluster cores and can be coupled to the cooling gas and therefore to feedback. CO has been detected in the centre of two nearby clusters with extreme X-ray cooling rates; a radiative cooling time < 1 Gyr and a star formation rate of 10–100$M_\odot$/yr for the central radio galaxy were derived. The bulk of the cold gas is centrally condensed and has a similar spatial extent to the star formation.

Observations of two extremely obscured luminous infrared galaxies (LIRGs) with very large obscuration and hidden compact infrared cores show a rich, hot-core-like chemistry with vibrationally excited HC_3N, HNC and HCN. In NGC 1266, an interacting galaxy, we are witnessing a rapid cessation of star formation, with a dense molecular gas outflow rate of ~ 100 $M_\odot$/yr, much larger than the star formation rate. An AGN is the likely driver of the outflow, and shocked molecular gas is located near the launch point of the outflow, as seen in ALMA multi-transition SiO observations. The detection of other molecular species with ALMA will help build a more complete chemical picture of NGC 1266.

High redshift sources

The redshifts of very high-z ($z > 5$) galaxies leads to fuller understanding of the objects responsible for the reionisation of the Universe. Their redshifts can be determined through detection of the [C II] line, which is the principal interstellar medium gas coolant, traces PDRs, and warm intergalactic and circumnuclear media, and CO lines (see Figure 4 for an example). [C II] is up to ten times more luminous than any other line in the far infrared/millimetre range, and at $z > 5$ the line is redshifted into ALMA bands. ALMA can detect [C II] from a galaxy with a star formation rate of only 5 $M_\odot$/yr at $z = 7$ in 1 hour (5σ in two channels). Furthermore, in low metallicity systems, as high-z objects are expected to be, the ratio [C II]/far-infrared is larger, i.e. increases with decreasing metallicity. Outflows can also be detected in such distant galaxies, as revealed by [C II] emission line profiles in a $z = 6.4$ quasar with velocities > 1000 km/s, size > 10 kpc and an outflow mass rate of ~ 3000 $M_\odot$/yr. The gas consumption timescale due to outflow may be less than the star formation timescale, highlighting the "quasar-mode" feedback process which inhibits further star formation and enriches the local intergalactic medium.

Gravitational lenses

The flux magnification provided by gravitational lensing enabled a spectroscopic redshift survey with ALMA to be performed in Cycle 0, targeting 26 sources from the South Pole Telescope using CO line detections (see Figure 4). 40% of these sources lie at $z > 4$. It appears that the fraction of dusty starburst galaxies at high redshift is far higher than previously thought. Two sources were found at $z = 5.7$, placing them among the highest redshift starbursts known, and demonstrating that large reservoirs of molecular gas and dust can be present in massive galaxies near the end of the epoch of cosmic reionisation. The ALMA detection of the arcs and source images of a beautiful gravitational lens, g15.v2.19, was also shown and discussed.

Prize poster competition

Given the large number of young participating students and postdocs, who presented many excellent results in the poster sessions, the Scientific Organising Committee decided to organise a competition for the best posters amongst them. The poster prize committee, composed of the overview speakers and the project scientists, awarded three prizes for the best science posters to: E. Akiyama for the analysis of the SV data on the protoplanetary disc around the

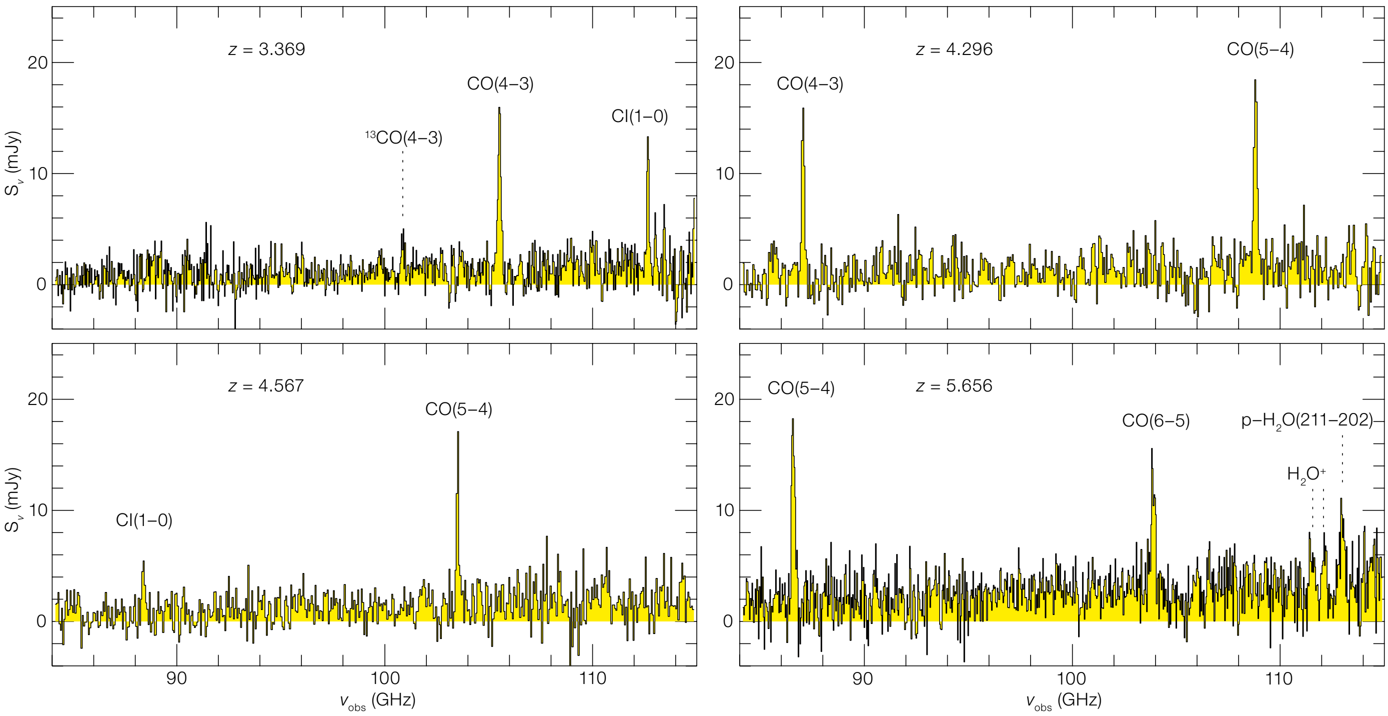

Figure 4. Example ALMA Band 3 spectra of gravitationally lensed submillimetre galaxies selected from the South Pole Telescope survey (Weiss et al., 2013). The spectra demonstrate the sensitivity of ALMA and the richness of the survey with detections of ^{12}CO, ^{13}CO, C I, H_2O and H_2O^+.

intermediate-mass pre-main sequence star HD 163296; R. Herrera-Camus, for the important work on the calibration of the [C II] line as a star formation tracer in the deep Universe; and M. McCoy for the study on the Early Science absorption spectrum of the nearby active galactic nucleus of Cen-A. Each of the three winners received an ALMA coffee mug, as a useful tool for the long hours to be spent on the scientific interpretation of the ALMA data, and a copy of the book *Cerca del cielo*, to remind them of the beauty and biological richness of the region of northern Chile that hosts the ALMA Observatory. Two posters describing important technical developments for ALMA also received a special mention: A. Avison for his work on the Observation Support Tool and H. Nagai for the description of the status of ALMA polarisation observations.

The practical organisation of the meeting was a great success, thanks to the efforts of the local organising committee at the JAO: Mariluz Calderón, Ann Edmunds, Valeria Foncea, Itziar de Gregorio Monsalvo, Violette Impellizeri, Hanifa Nalubowa, and Gautier Mathys (chair). The conference was co-sponsored by ESO, NAOJ, NRAO, the EC-FP7 Radionet-3 project and CONYCIT.

References

Casassus, S. et al. 2013, Nature, 493, 191
Sánchez-Monge, Á. et al. 2013, A&A, in press
Weiss, A. et al. 2013, ApJ, in press

Links

[1] First Year of ALMA Science conference website: http://www.almasc.org/

ESO/B. Tafreshi (twanight.org)

A recent view of the Chajnantor Plateau and ALMA taken from the nearby peak of Cerro Chico. See Picture of the Week 24 December 2012 (potw1252a).