Special Contribution
ALMA and its Observational Achievements: Unveiling the Mysteries of the Dark Universe

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1. Introduction

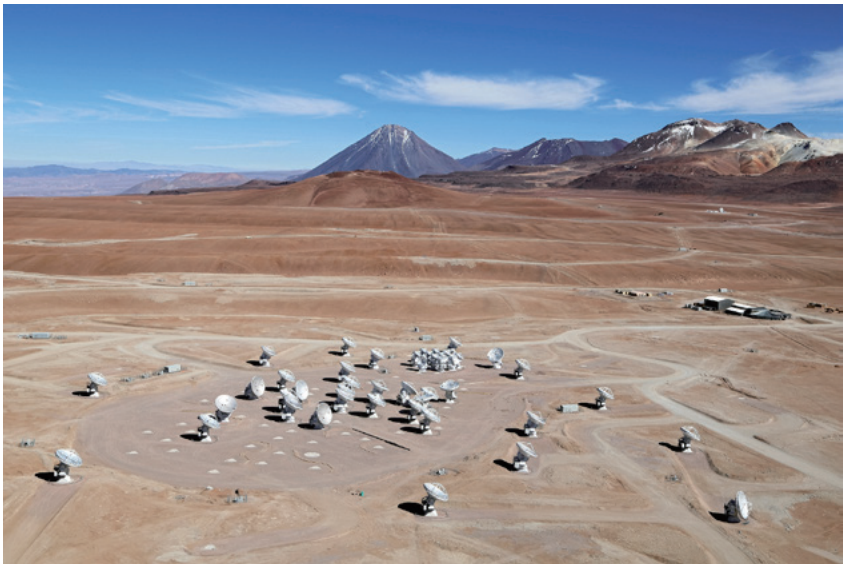
How did our solar system come to be? How and when was the Milky Way, our solar system's home galaxy, born, and how has it evolved? How much matter from which life originates is floating in space? These questions, which have been pondered for several centuries, are now being pursued with the help of the ALMA telescope, which is jointly operated by 22 countries and regions including Japan.[1)]

The ALMA telescope combines 66 parabola antennas functioning as a huge radio telescope with a virtual diameter of approximately 16 km. It has been constructed in northern Chile on the Chajnantor Plateau at an altitude of 5,000 m (**Figure 1**). Baked in strong sunlight with a level of oxygen half that at ground level, this is a harsh environment for people. Despite its location, the ALMA telescope is said to be mankind's newest "window" for peering into the depths of the universe.

This paper introduces a variety of advanced technologies used by the ALMA telescope and new cosmic structures that have come to be observed with ALMA.

2. Radio astronomy for observing the "invisible universe"

The ALMA telescope captures radio waves



Credit: Clem & Adri Bacri-Normier (wingsforscience.com) / ESO

Figure 1
ALMA telescope.

rather than visible light. Whereas visible-light wavelengths range from 400 to 800 nm, the International Telecommunication Union (ITU) defines electromagnetic waves with wavelengths greater than 100 μm (equivalent to a frequency of less than 3 THz) as radio waves. Electromagnetic waves with different wavelengths have different radiation sources. Visible light is emitted mainly from stars and high-temperature gas energized by stars, and radio waves are emitted from extremely low-temperature interstellar matter having an absolute temperature of 10 K (−263°C) as well as from high-temperature gases ejected from supermassive black holes. Making observations of space at diverse wavelengths such as those of visible light, radio waves, X-rays, and ultraviolet rays enables astronomers to investigate various types of celestial bodies and phenomena, leading to a deeper understanding of the universe.

Radio waves have various wavelengths within different wavelength bands corresponding to different types of observable matter. The radio waves observed by the ALMA telescope introduced here lie in the wavelength band from 10 mm to 0.3 mm and are therefore called millimeter waves and submillimeter waves. This band is suitable for observing the low-temperature interstellar matter mentioned above. Conversely, most of the stars in the night sky cannot be observed at those wavelengths. What are visible with millimeter and submillimeter waves are dark clouds floating between stars, or interstellar matter, which consists of fine dust particles 1 μm or smaller and gas made up mainly of hydrogen. This gas includes various types of molecules such as carbon monoxide, ammonia, and methanol, each of which emits radio waves at particular wavelengths. The wavelengths of radio waves arriving from space can be compared with the wavelengths of radio waves previously measured in the laboratory to identify the types of molecules contained in the observation target. In addition, the intensity of those radio waves can be used to estimate the density and temperature of those molecules. Dust particles, meanwhile, emit radio waves with a wavelength distribution corresponding to the temperature of those particles. Interstellar matter can be called the material of stars and planets as well as the material of galaxies, the aggregates of stars. Making detailed observations of radio waves emitted from interstellar matter enables researchers to pursue the cosmic mysteries mentioned at the beginning of this paper.

3. ALMA—the ultimate radio telescope

The history of radio astronomy spans about 85 years during which many radio telescopes have been constructed. The ALMA telescope can be said to be one of the greatest achievements of this effort. The following provides an overview of the ALMA project.

The formal name of the ALMA telescope is Atacama Large Millimeter/submillimeter Array (ALMA). "Atacama" refers to the Atacama Desert, the region where the ALMA telescope is located. This region occupies the northern half of Chile, a long and narrow country in South America running north and south along the Pacific coast. It is one of the most arid locations in the world with annual rainfall of less than 100 mm. The ALMA telescope has been constructed in this desert on a 5,000-m-high plateau in the Chilean Andes. Following a survey of observation conditions in various regions around the world, this location was identified as the most suitable for millimeter-wave and submillimeter-wave observations.

The word "array" in the formal name of ALMA is synonymous with "interferometer," which means a mechanism for combining multiple parabola antennas in a way that makes them function as a single and huge radio telescope. In this regard, the resolution of a telescope is proportional to its diameter and inversely proportional to the wavelength of the electromagnetic waves to be observed. Although there is a technical limitation on the diameter of a single telescope, multiple antennas can be interconnected to overcome it. This is the basic idea behind an interferometer. The ALMA telescope comprises 66 antennas spread out over approximately 16 km, thereby achieving an effective resolution equivalent to that of a telescope with a diameter of 16 km. The resolution of a telescope is expressed in terms of the angle that can be distinguished with the telescope. The ALMA telescope has a resolution of 0.01 arcseconds (1 arcsecond = 1/3,600 of a degree), which corresponds to eyesight capable of distinguishing a U.S. penny from 500 km away. This is ten times the resolution of the Subaru Telescope and Hubble Space Telescope.

It has become common for such advanced scientific projects to be operated as an international collaboration. The ALMA telescope is no exception—it is jointly run by an East Asia group consisting of Japan, Taiwan, and South Korea, a North America group consisting of the United States and Canada, the European Southern Observatory representing 16 countries, and Chile, its location, for a total of 22 countries and regions. The various components of the telescope described in the next section were developed and delivered on a trilateral basis, and their staffing and operating expenses are shared accordingly. The East Asia group contributed about one-fourth to the total effort.

4. Technologies used in ALMA

The ALMA telescope is a complex piece of equipment made up of a wide variety of elements, but the three main types of components are antennas, receivers, and correlators (**Figure 2**). This section briefly describes the technologies they use.

As described above, ALMA consists of 66 antennas in total within which there are actually two systems. The first is a "12-m array" consisting of fifty 12-m antennas, and the second is the "Atacama Compact Array (ACA)" consisting of four 12-m antennas and twelve 7-m antennas. The United States and Europe developed the antennas in the 12-m array while Japan developed the ones in the ACA. The ACA is also called the "Morita Array" in honor of Koh-ichiro Morita, Professor of the National Astronomical Observatory of Japan (NAOJ), who passed away in Chile while making important contributions to its design.

Figure 2
Japan's contributions to ALMA telescope.
(Upper left) 12-m antenna, (lower left) 7-m antenna, (upper right) 3 types of receivers, (lower right) ACA correlator.

The most important role of each of these antennas is to precisely track the celestial body targeted for observation and to focus the radio waves irradiating the antenna with high efficiency. Tracking performance and mirror accuracy are therefore important. In contrast to ordinary optical telescopes, each antenna making up ALMA is not enclosed in a dome, and actual observations are carried out in both daytime and nighttime hours. A variety of measures have therefore been devised to ensure that each antenna maintains its lock on the target even during observations under harsh conditions such as intense sunlight, dramatic temperature changes, and strong winds. These measures differ in accordance with the country or company that developed the antenna. The Japanese-made antennas, for example, have several key features: (1) use of carbon fiber reinforced plastic to reduce thermal deformation in the truss structure of the primary reflector (12-m antennas), (2) use of low-cost iron to hold down costs (7-m antennas) and fans to force air through the truss structure of the primary reflector to stabilize the temperature and counteract iron's susceptibility to thermal stress (7-m antennas), and (3) use of a frame structure independent of the chassis inside the antenna mount section and a metrology system to measure the gap between the frame structure and chassis in real time and instantly compensate for any deformations (both 12-m and 7-m antennas). These features enable the antennas to achieve a directional accuracy of 1/6,000 of a degree and have a reflector surface that deviates from an ideal parabolic surface by less than 25 μm (about 1/3 the size of a strand of hair), resulting in high antenna accuracy. The Japanese-made antennas were manufactured in a collaborative effort between NAOJ and more than 80 companies, led by Mitsubishi Electric Corporation.

If we were to compare an ALMA antenna with an ordinary camera lens, the component corresponding to the imaging element in the camera would be the "receiver." The radio waves observed by ALMA were divided into ten wavelength bands, and a receiver with an optimal design for each band was developed. A set of these ten receivers is housed in a cryogenically cooled tank (cryostat) and installed in each antenna. The NAOJ was assigned to develop the receivers for three wavelength bands (bands 4, 8, and 10, corresponding to wavelengths of approximately 2 mm, 0.6 mm, and 0.3 mm) and then to manufacture 73 sets (66 for installation in antennas and 7 for backup) for a total of 73 receivers per band. The heart of each receiver is a superconductor-insulator-superconductor device having a sandwich structure consisting of a thin film of aluminum oxide about 1-nm thick placed between two niobium superconductors. A clean room equipped with ultraviolet exposure equipment capable of fine circuit fabrication like that used in semiconductor manufacturing was set up in the NAOJ Advanced Technology Center, enabling the development of world-class devices for ALMA with stable mass production. The technical staff of the Center was particularly active in the design and assembly of the receivers and in the design and partial manufacturing of the mirrors and other optical components.

The radio waves from space are converted into electrical signals by a receiver, digitized, and passed through optical fiber to a “correlator” that operates as a specialized computer. The role of this correlator is to synthesize the signals output from the multiple antennas to make the entire array function as a single telescope (correlation processing) and to extract signal frequency information to obtain a radio wave spectrum (Fourier transform). Housed in indoor racks, the correlator is hardly noticeable, but it is an essential element that can be called the brains of this interferometer.

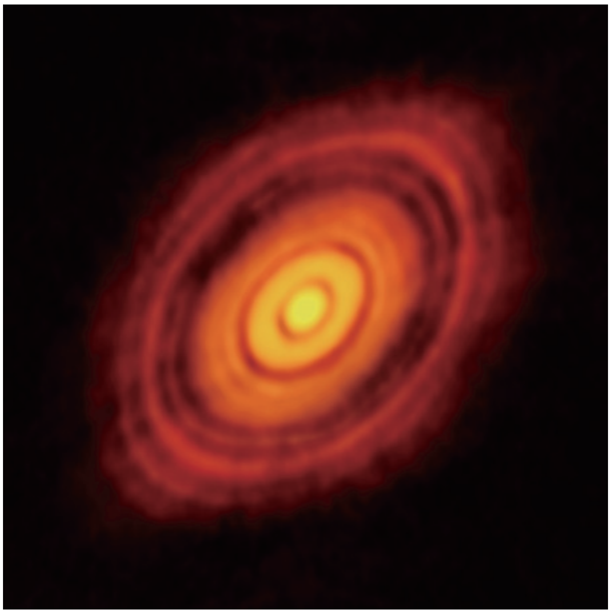
The ALMA telescope has two correlators: the “64-element correlator,” which processes signals from the U.S. and European antennas, and the “ACA correlator,” which processes signals from the Japan-developed ACA. The latter was developed and manufactured jointly by Fujitsu, NAOJ, and other parties. The project team that developed the ACA correlator had to deal with a number of difficulties not the least of which was the huge volume of data that had to be processed. To deal with this problem, the ACA correlator inputs data from 16 antennas at a rate of 256 GB/s and performs 120 tera-operations per second in real time against this incoming data. At the time of installation, the correlator processing speed was equal to that of the fourth fastest supercomputer in the world (and to that of the fastest supercomputer in Japan). It uses 5,152 field-programmable gate array (FPGA) chips to achieve flexibility and lower costs.

Another difficulty that the team had to face was that the ACA correlator had to be installed within facilities located on a mountaintop at an altitude of 5,000 m. The atmospheric pressure there is half that at sea level, resulting in a drop in air-cooling efficiency. To solve this problem, an efficient cooling method that could level out the heat generated within the correlator was proposed and then evaluated using a lengthy test run in a low-pressure chamber. Additionally, a diskless configuration was adopted given that the failure rate of hard disks is higher in a low-pressure environment. This diskless equipment is activated by a network boot from a computer installed in the Operations Support Facility at the foot of the mountain at an altitude of 2,900 m. Finally, as this correlator location does not facilitate maintenance, a variety of measures were devised such as a remote maintenance function operated from Japan.[2)]

5. Milestone ALMA achievements

The ALMA telescope began scientific observations in September 2011 in accordance with proposals from researchers around the world. As of July 2016, more than 400 ALMA-related peer-reviewed papers have been published. The following introduces several milestones in observations made with ALMA.

A key achievement of ALMA surrounds the observation of HL Tauri, a young star in the constellation Taurus.[3)] This star, observed in a very early stage of its life (about a million years old), is located at the center of a disk of gas and dust (protoplanetary disk). The image obtained by ALMA at a resolution of 0.03 arcseconds (corresponding to eyesight capable of distinguishing a U.S. penny from 170 km away.) showed, in particular, a disk consisting of a series of concentric rings (**Figure 3**). This was the first time that an image of a disk with a multi-ring structure was captured in such detail. On observing this image for the first time, the author himself mistook it for an artist’s illustration. A number of theories have been advanced as to the origins of these concentric rings, but the origin has yet to be determined. One theory is that huge planets already in the process of being formed exist within the gaps between the rings and that such gaps formed as those planets “swept up” dust by gravitational force. This gap-forming mechanism itself agrees with prior theoretical predictions, but what was unexpected in



Credit: ALMA (ESO/NAOJ/NRAO)

Figure 3
Disk surrounding a young star HL Tauri in the constellation Taurus.

this observation was how planets large enough to create such gaps could have already been formed at such a young age of a million years. If this theory were correct, it would mean that planetary formation progresses over a shorter time frame than thought and that existing theory would have to be reevaluated. Another theory is that the rings were formed by the collision, merging, and breakdown of dust as opposed to planets, and another is that the rings were formed by friction acting between the gas and dust in the disk. It may be appropriate to say that high-definition images like this one can also make for more mysteries to be solved. This, however, is the true pleasure of research.

The ALMA telescope also targets the far reaches of the universe for observation. However, the propagation of electromagnetic waves through space takes time, so observing the far reaches of the universe is synonymous with observing the past. This is like using a time machine to rewind the history of the universe by more than 13 billion years, which means that we can witness how the galaxies, which include several hundred billion stars, were formed and how they have evolved. ALMA has been used to observe a number of galaxies that have been in existence for about 13 billion years. An important objective in observing a galaxy is determining its composition. Familiar elements like carbon and oxygen (called "heavy elements" in astronomy) created by nuclear fusion reactions inside stars have been scattered in space through the death of stars. In short, heavy elements have gradually accumulated in space along with the generational changes in stars. Investigating exactly how heavy elements accumulate in this way can shed light on the evolution of galaxies and the history of star formation. For example, oxygen was discovered in a galaxy from 13.1 billion years ago with the ALMA telescope.4) Galaxies of similar age with extremely small amounts of dust and carbon atoms have also been found. The ALMA telescope, with its high sensitivity, is helping to explain how the universe evolved through its observations of many ancient galaxies.

In addition, ALMA is now also being used to search for organic molecules in space that may be related to the origin of life. How life on Earth began is still unclear, but it has been pointed out that complex organic molecules (such as amino acids) formed in space may hold the key to solving this puzzle. The high sensitivity of ALMA should enable it to detect radio waves emitted by amino acid molecules. If such amino acids were abundant in planet-forming regions, such as the region where HL Tau was formed, perhaps they could be swept up by planets forming in those regions, providing an opportunity for the creation of life. Of course, while the origin of life is hardly that simple, ALMA should at least be able to clarify the extent to which this material exists in the universe. Actually, ALMA has yet to find any amino acids, but it has discovered the sugar molecule glycolaldehyde, a precursor to amino acids, in the vicinity of the protostar IRAS 16293-2422.5) In addition, observations of the Sagittarius B2 star-forming region revealed an abundance of an organic molecule having a branched carbon backbone as in amino acids.6)

Other achievements with ALMA include the discovery of skewed concentrations of organic molecules in the atmosphere of Saturn's moon Titan and detailed imaging of the structure of gas shed from a dying star. In addition, ALMA has been used to measure the mass of a massive black hole by analyzing the motion of gas rotating about it. In this way, ALMA has made it possible to explain a variety of new structures in celestial bodies. The ALMA telescope can be applied to an extremely broad range of astronomical bodies and phenomena, and in this capacity, it is revolutionizing a variety of fields in astronomy.

6. Conclusion

The official slogan of the ALMA project is, "In Search of our Cosmic Origins." It is said that the ALMA effort, which seeks to solve the mysteries surrounding the birth of galaxies and planets, also aims to find mankind's roots in the universe. Achieved by combining the strengths of many countries around the world and of people from those countries, the ALMA telescope project continues to make observations in a very rugged environment to help solve the various universal mysteries of mankind. We can look forward to even more amazing results in the years to come.

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