Inter-University Research Institute Corporation
National Institutes of Natural Sciences

National Astronomical Observatory of Japan

NAOJ 2019-2020

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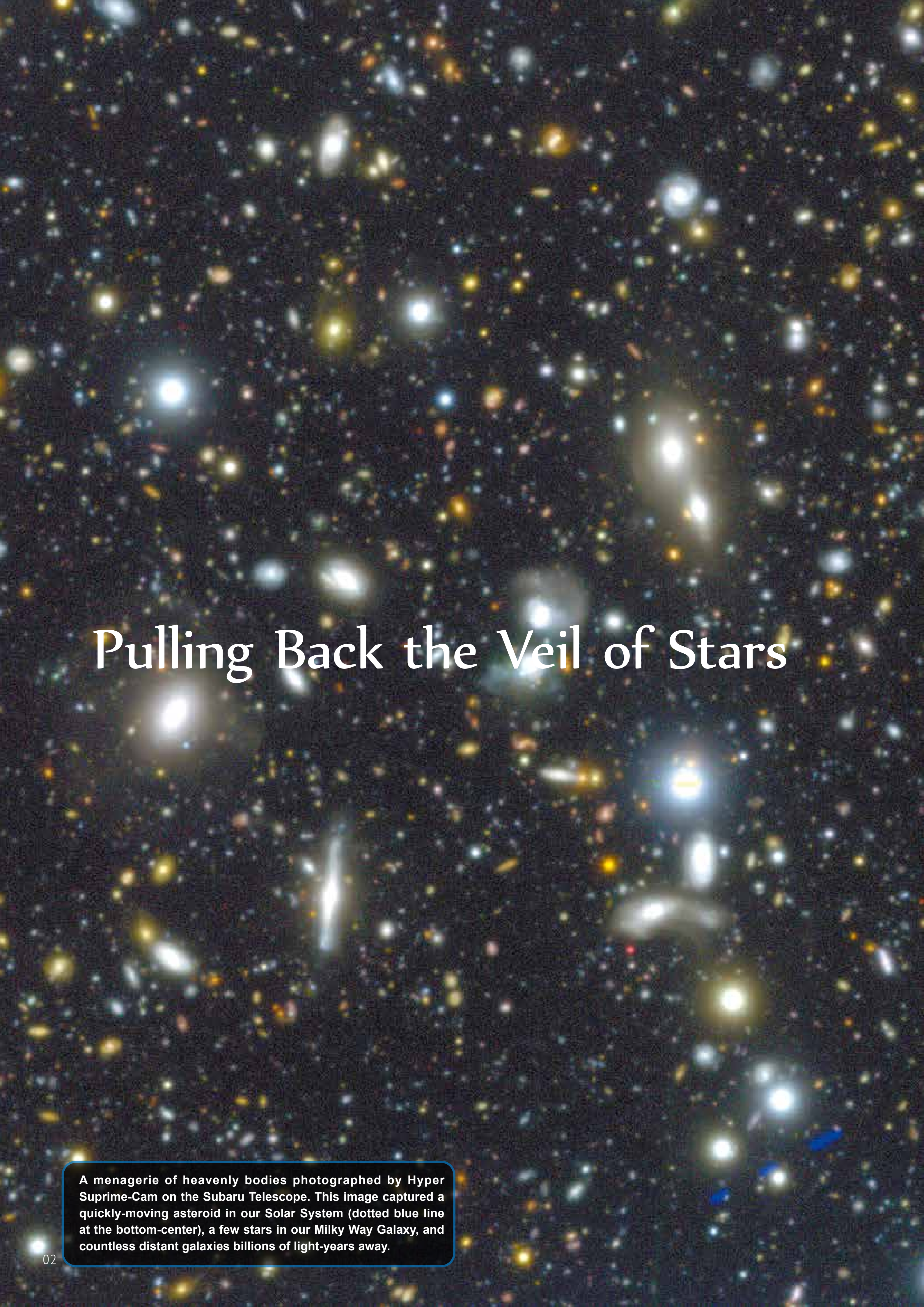

Pulling Back the Veil of Stars

A menagerie of heavenly bodies photographed by Hyper Suprime-Cam on the Subaru Telescope. This image captured a quickly-moving asteroid in our Solar System (dotted blue line at the bottom-center), a few stars in our Milky Way Galaxy, and countless distant galaxies billions of light-years away.

Astronomy is one of humanity's oldest sciences. It started with making calendars for farming and hunting, and has now grown to include the fundamental desire held by everyone to “understand our place in the grand scheme of the Universe.” Modern perspectives on the Universe, primarily the “Big Bang Theory” established in the latter half of the 20th century, laid the scientific foundation to understand the unified dynamism of material evolution, explaining the Earth in the context of the history of the Universe, life in the context of the history of the Earth, and humanity in the context of the history of life. And with the start of the new century we have entered the age of investigating planets outside the Solar System and examining the possibility of extraterrestrial life. By observing various hitherto unknown cosmic phenomena, NAOJ plays a role in "creating new views of nature" which will connect the Universe, life, and ourselves together.

Cover Photo: the Moon and Milky Way over ALMA (photographer: Akira Kawamura)
Back Cover Photo: the Pleiades ("Subaru" in Japanese) and the Subaru Telescope (photographer Mr. Pablo McLoud - Subaru Telescope)
· Production Staff: Masaaki Hiramatsu (Editor in Chief), Hiroyuki Takata, Maki Kubo, Ramsey Lundock, Ryo Sato (NAOJ Publications Office)
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Subaru Telescope

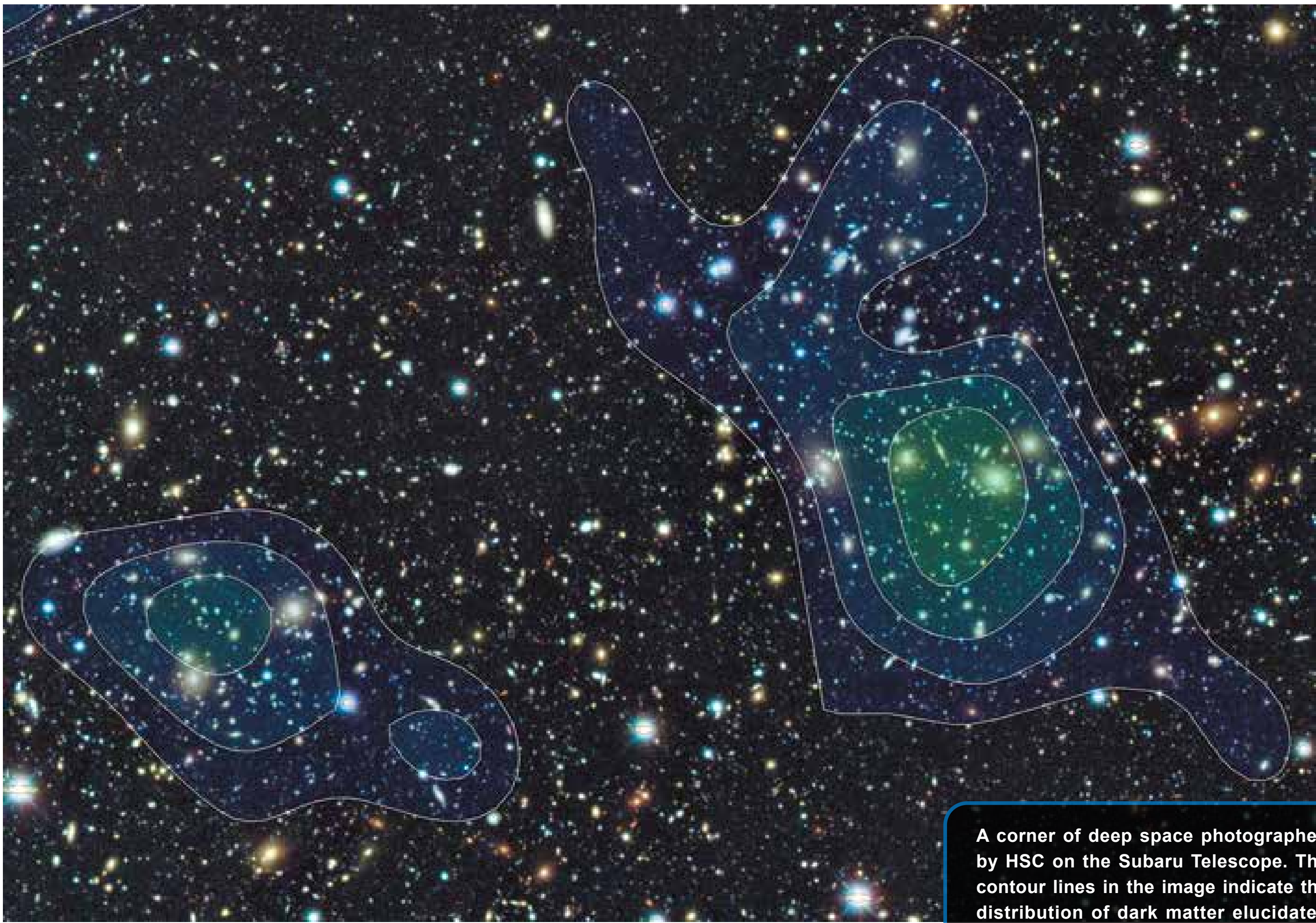
An Eye Scanning the Breadth and Depth of the Universe

NAOJ's optical-infrared Subaru Telescope located near the summit of Maunakea in Hawai‘i boasts a world-class aperture of 8.2 meters. Making maximum use of this potential, the Subaru Telescope scans the breadth and depth of the night sky to investigate the origin of cosmic structure.

The summit region of Maunakea in Hawai‘i: the silhouette of the Subaru Telescope enclosure floating above a sea of clouds on a moonlit night.

The Subaru Telescope illuminated by moonlight. A 3 meter long, 3 ton digital camera, Hyper Suprime-Cam (HSC), is mounted at the top of the telescope structure (prime focus). The Subaru Telescope is the only 8–10 meter class telescope in the world capable of mounting a camera at its prime focus with a wide field-of-view. The large light gathering power and sharp image resolution enabled by the 8.2 meter primary mirror combined with HSC's wide field-of-view make the Subaru Telescope unique in its capabilities. HSC's field-of-view is nine times the area of the full moon, allowing us to photograph countless galaxies in each frame and investigate the nature of the mysterious dark matter.

Subaru Telescope Science 01



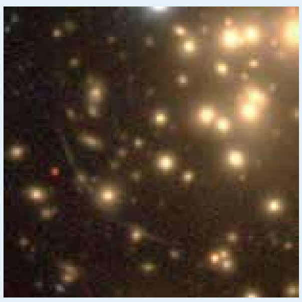
A corner of deep space photographed by HSC on the Subaru Telescope. The contour lines in the image indicate the distribution of dark matter elucidated by measuring the gravitational lensing effect.

Subaru Telescope

Investigating the Mysteries of Omnipresent Dark Matter and Dark Energy

The Universe is filled with a mysterious substance known as “dark matter”; and a mysterious energy known as “dark energy” is accelerating the expansion of the Universe. It is necessary to unveil the nature of dark matter and dark energy in order to understand the evolution and the physics of the Universe.

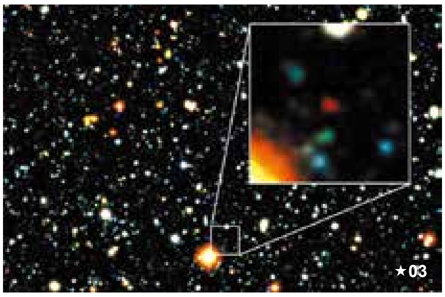
One way to do that is by using gravity. By using gravitational lensing, a phenomenon where gravity causes light to curve, we can investigate the distribution of dark matter. With its ultra-wide-field-of-view observation capability, the Subaru Telescope excels at these observations. Boasting 870 million pixels, Hyper Suprime-Cam (HSC) can capture a great number of galaxies in each picture. By precisely measuring the distortion in the galaxy images we can elucidate the 3D distribution of dark matter. In addition, by using the Prime Focus Spectrograph capable of observing up to 2400 objects simultaneously to accurately measure the distances to many galaxies, we can obtain the 3D distribution of dark matter at high precision. Then, by comparing the 3D dark matter distribution to theoretical models of structure formation and the expansion of the Universe we can determine the characteristics of dark matter and dark energy.



The galaxy cluster Abell 1689 photographed by HSC on the Subaru Telescope. The gravity of the cluster bends the light from background galaxies, causing the images of those galaxies to appear stretched.

Subaru Telescope Gallery


★02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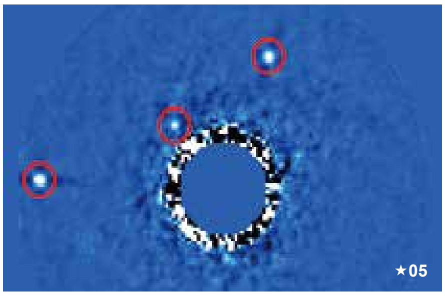
★01


★04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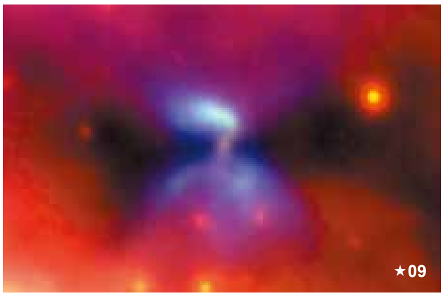
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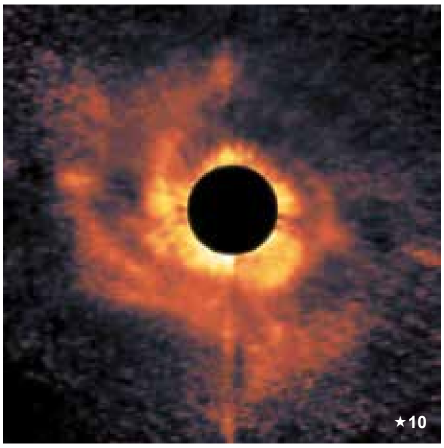
★10


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★13


★14

★01 Star forming region S106 IRS4
★02 The Subaru Telescope
★03 The galaxy IOK-1 (red object in the center of the inset) discovered 13 billion light-years away
★04 The snowy summit of Maunakea (the Subaru Telescope enclosure is visible on the right)
★05 Three planets (red circles) orbiting the star HR8799
★06 Subaru Telescope Control Room
★07 Starburst galaxy M82
★08 The snowcapped summit of Maunakea seen from Hilo Bay
★09 Protostar M17-S01
★10 Protoplanetary disk of the young star AB Aurigae
★11 Close-up image of M31 (the Andromeda Galaxy)
★12 Wide Field Corrector of Hyper Suprime-Cam
★13 The Subaru Telescope enclosure with the laser beam for adaptive optics (photograph: Dr. Sebastian Egner, Subaru Telescope, NAOJ)
★14 Galaxy Cluster "Stephan's Quintet"

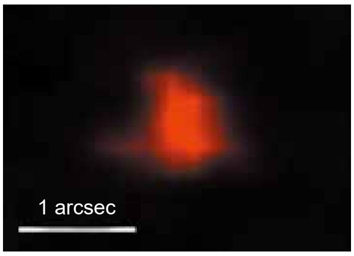
The Subaru Telescope is located in the summit region of Maunakea at an altitude of 4200 meters. It is one of the best sites in the world for astronomy with many clear nights and stable air flow. Maunakea hosts 13 telescopes from 11 countries, one of the largest collections of leading-edge astronomy observation facilities in the world. Through 20 years of observations since its first light in 1999, the Subaru Telescope has greatly advanced Japanese astronomy. As of the end of 2018, it has contributed to an outstanding total of 1936 papers and 126 doctoral theses. It also appears from time to time in textbooks and various media outlets, making it one of the widely recognized symbols of Japanese science.

Subaru Telescope

Subaru Telescope Science 02

Unlocking the Mysteries of Galaxy Formation and Evolution

The Subaru Telescope, with its ability to survey large expanses of space with its ultra-wide-field-of-view, has vigorously conducted efficient searches for very distant objects. Many times over, it has set the record for the "most distant galaxy ever observed." Each one bringing us a step closer to the beginning of the Universe. And now, Hyper Suprime-Cam is going to photograph 400,000 galaxies within the first 1 billion years after the Big Bang. This will provide vital clues for understanding the growth of galaxies.
The wavelengths of light from the distant Universe are stretched by the expansion of space. Observing infrared light, with wavelengths longer than visible light, allows us to observe more distant objects. Currently we are planning a wide-field, high-resolution infrared camera to be mounted on the Subaru Telescope. With it, we expect to discover many newborn galaxies in the early Universe. Follow-up observations of the discovered objects using ALMA or the Thirty Meter Telescope (TMT) currently under construction will elucidate when the first stars formed and the effects the newborn stars had on their surrounding environment, helping to solve the mysteries of galaxy formation.



Suprime-Cam/Subaru Telescope image of galaxy SXDF-NB1006-2. When first discovered in 2012, this object set the record for the most distant heavenly body ever observed: 13.06 billion light-years away.

Power-up to Super-Subaru with Colorful New Instruments

The Prime Focus Spectrograph (PFS) is mounted at the prime focus of the Subaru Telescope. It can simultaneously take the spectra of up to 2400 objects across its 1.3 degree diameter ultra-wide-field-of-view. [Photo: one of the PFS camera units assembled at Johns Hopkins University. (credit: Yuki Moritani/IPMU)] We are also investigating the Ultra-wide Laser Tomographic Imager and MOS with AO for Transcendent Exploration (ULTIMATE) with a field-of-view 40 times wider than the Hubble Space Telescope. The combination of HSC, PFS, and ULTIMATE will push the Subaru Telescope's wide-field capabilities beyond the limits of where others can follow. (Refer to page 27.)

Subaru Telescope

Subaru Telescope Science 03

Discovery of Earth-like Exo-Planets

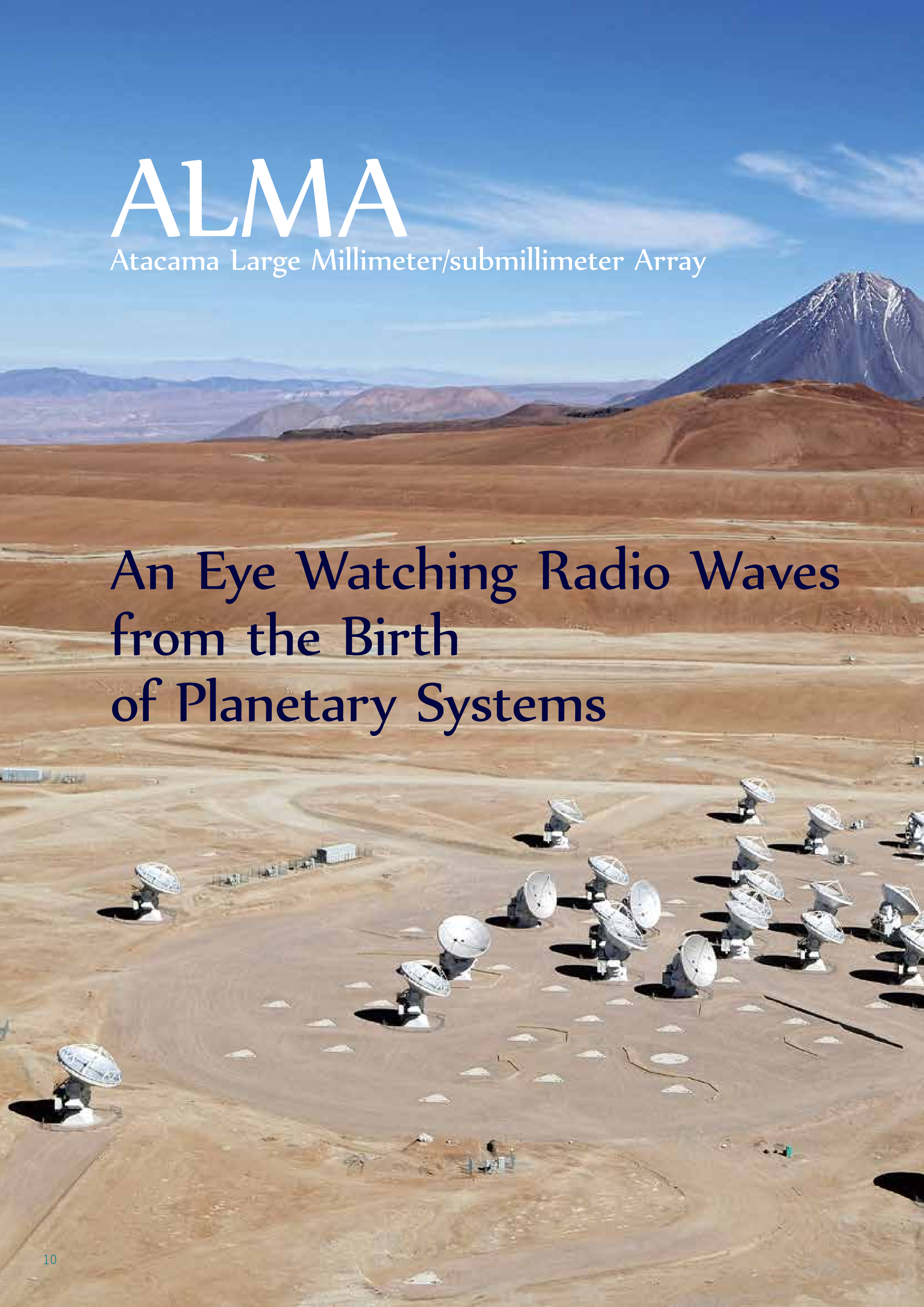
Over 4000 exo-planets have been discovered to date. The Subaru Telescope is also displaying its strength through observations of those exo-planets. In 2013, making the best use of the Subaru Telescope's high sensitivity, it directly imaged the dimmest planet at that time.
Among exo-planets, Earth-like planets are garnering attention. Direct imaging of these comparatively small planets is difficult for 8-meter class telescopes. But by using high-dispersion spectroscopic observations they can discover small planets through the wobble induced in the host star by the orbital motion of the planet. At the Subaru Telescope we have installed a near-infrared high-dispersion spectrometer to pursue the search for Earth-like exo-planets. The discovered exo-planets will be observed with the Thirty Meter Telescope (TMT) to analyze the atmospheric composition, and enable us to search for signs of life, advancing the field of astrobiology. (Refer to page 25.)

The exo-planet GJ 504b (dot in upper right) discovered by the Subaru Telescope. The bright light of the central star has been artificially concealed, but some of the light still leaks out around it. GJ 504b is the dimmest, coolest exo-planet ever observed. It is a giant planet with a mass 3~5 times that of Jupiter.

ALMA

Atacama Large Millimeter/submillimeter Array

An Eye Watching Radio Waves from the Birth of Planetary Systems



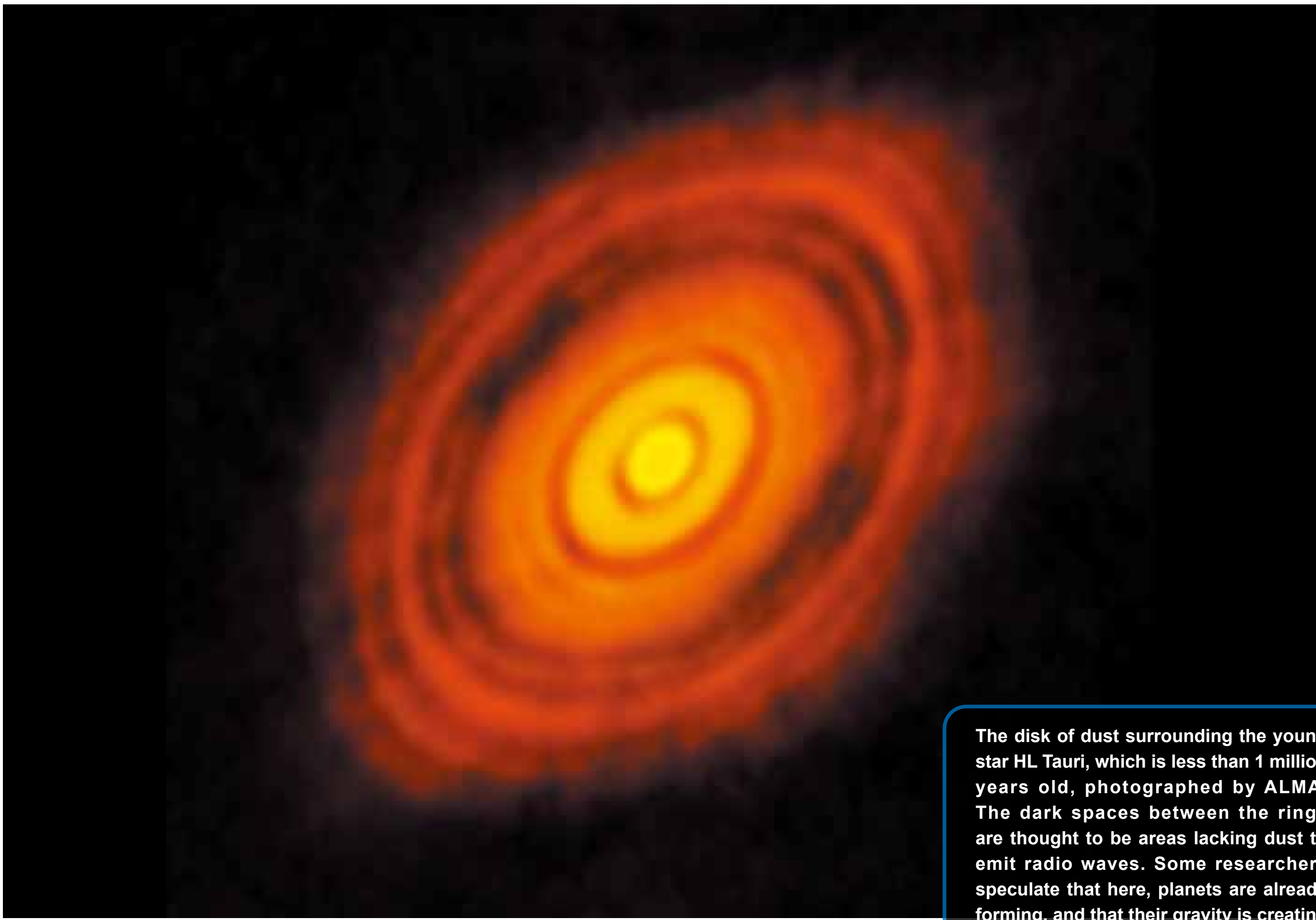
Located in the Atacama Desert, ALMA is one of the world's highest capability radio telescope arrays, achieved through an international collaboration including NAOJ, North America, Europe, and other partners. The 66 individual antennas function together as a single giant radio telescope. Its radio observations show us a face of the Universe impossible to see with visible light.

The ALMA array is deployed in the dry Atacama Desert at an altitude of 5000 meters. ALMA uses a technique called "radio interferometry" to connect multiple parabolic antennas together to act as a single, giant radio telescope. The 66 antennas can be deployed across a range of up to 16 kilometers, achieving the same image resolution as a 16 kilometer diameter telescope would. The resolution is equivalent to 120000/20 vision in terms of eyesight, which corresponds to being able to see a penny in Los Angels from San Francisco. With this overwhelming resolution ALMA can capture clear images of the sites of planet formation.

[photo: Clem & Adri Bacri-Normier (wingsforscience.com) ／ESO]

The many parabolic antennas of ALMA. Built to withstand the harsh sunlight and temperature fluctuations of the desert, the antennas were developed by combining the technological know-how of the various partners.

ALMA Science 01



The disk of dust surrounding the young star HL Tauri, which is less than 1 million years old, photographed by ALMA. The dark spaces between the rings are thought to be areas lacking dust to emit radio waves. Some researchers speculate that here, planets are already forming, and that their gravity is creating the gaps by sweeping up the dust.
Credit: ALMA (ESO/NAOJ/NRAO)

ALMA

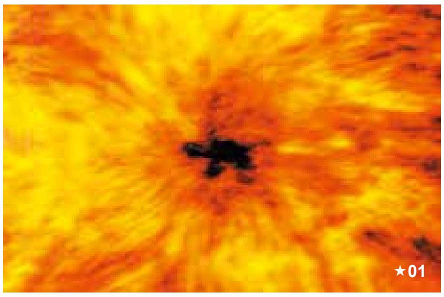
Unlocking the Mysteries of Star and Planet Formation

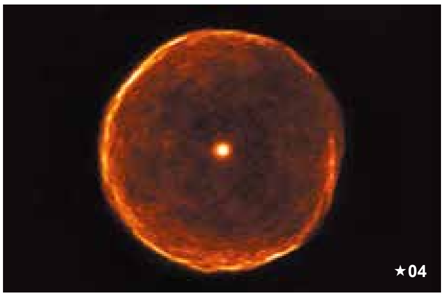
Newborn stars and planets still in the process of forming lurk in the night sky. The diffuse clouds of interstellar gas and dust are the material for stars and planets. These clouds gradually compact, and in their centers stars and planets are born. These newborn stars are hidden inside the parent clouds, where they cannot be observed with visible light. But radio waves can escape from the clouds of gas and dust. ALMA collects these weak radio waves to unlock the mysteries of star and planet formation.

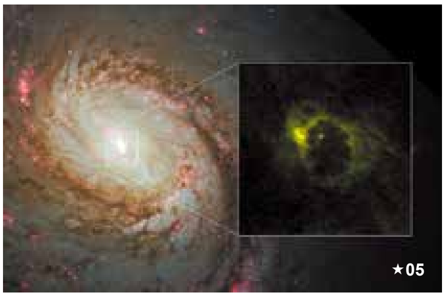
Disks comprised of gas and dust revolve around young stars, with ages between 100 thousand and 10 million years. These protoplanetary disks are the sites of planet formation. ALMA's high angular resolution has revealed concentric ring structures in the disks, as well as disks with spiral or crescent shaped dust distributions. By starting to image the sites of planet formation in detail, we are coming to understand the formation mechanism of the various planetary systems in the Universe, including our own Solar System.

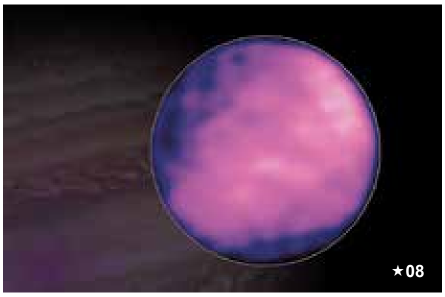
The spiral shaped protoplanetary disk around the young star Elias 2-27 photographed by ALMA. Credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

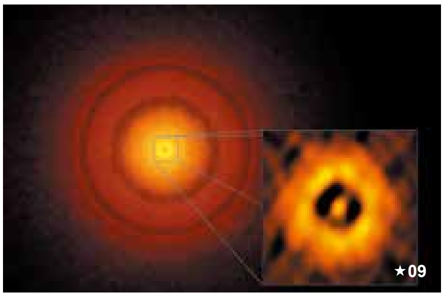
ALMA Gallery

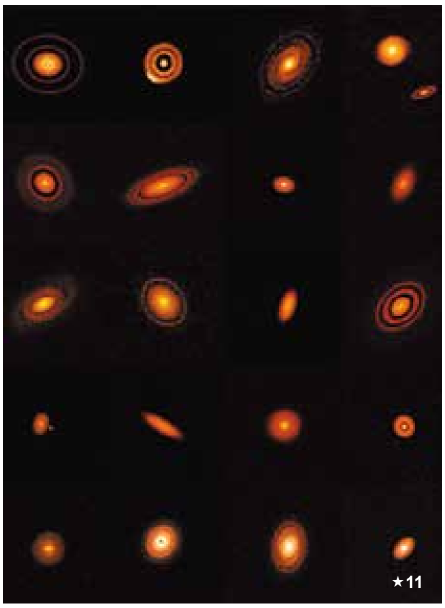












★01 A sunspot photographed by ALMA
★02 ALMA Trilateral Agreement Signing Ceremony
★03 ALMA Morita Array
★04 ALMA image of the gas around the star U Antliae
★05 Close-up of the center of spiral galaxy M77
★06 ALMA Control Room
★07 A 7-meter antenna being transported to the Array Operations Site
★08 The surface of the Jovian moon Europa
★09 Dust disk around TW Hydrae
★10 Vicuna
★11 Twenty sites of planetary system formation captured by ALMA
★12 Sunyaev-Zel'dovich effect in galaxy cluster RXJ1347.5-1145
★13 Antennae Galaxies

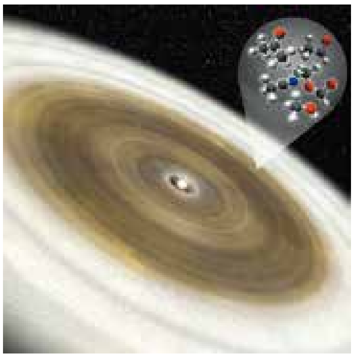
Credit: ★04 ALMA (ESO/NAOJ/NRAO)/F.Kerschbaum ★05 ALMA (ESO/NAOJ/NRAO), Imanishi et al., NASA/ESA Hubble Space Telescope and A.van der Hoeven ★08 ALMA (ESO/NAOJ/NRAO), S. Trumbo et al.; NRAO/AUI NSF, S. Dagnello; NASA/ESA Hubble Space Telescope ★09 S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO) ★11 ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello ★12 ALMA (ESO/NAOJ/NRAO), Kitayama et al., NASA/ESA Hubble Space Telescope ★13 ALMA (ESO/NAOJ/NRAO). Visible light image: the NASA/ESA Hubble Space Telescope ★All other images are credit: ALMA (ESO/NAOJ/NRAO)

ALMA is located in the Atacama Desert in northern Chile. The Atacama Desert is said to be one of the driest locations in the world, combined with the 5000 meter altitude, it is a harsh place to construct a telescope array. Because the radio waves ALMA observes (around 1 mm on the border between millimeter waves and submillimeter waves) are absorbed by water vapor, an extremely dry location is needed. In addition an area wide enough to array 66 antennas is needed. Started with the joint site survey by the international team of researchers from the early 1990s, currently 22 countries and regions are participating in the operation of ALMA, including Japan, Taiwan, and South Korea in East Asia; the United States and Canada in North America; the European Southern Observatory representing its Member States; and the host country of Chile.

ALMA Science **02**

Searching for the Building Blocks of Life in the Universe

ALMA can catch the radio waves emitted by various materials floating in space. Researchers are particularly interested in organic molecules connected to the origin of life. What kinds of molecules are found at the sites of planet formation around young stars? Can the organic molecules that become the seeds of life, for example amino acids, be found here? ALMA has discovered complex organic molecules and simple suger molecules around newborn stars, as well as elucidating the distribution of alcohol molecules in protoplanetary disks. If chemical reactions continue for the tens-of-millions of years it takes planets to form around young stars, what complexity of molecules can appear? Through comparison with the results from space exploration missions like Hayabusa2 in the Solar System, the planetary system we know best, ALMA will elucidate the evolution of the ingredients for life.



ALMA observed the protoplanetary disks surrounding young stars and found various organic molecules including methanol and acetaldehyde. Studies of organic molecules at the sites of planet formation will yield important clues about the origin of life.

One Unparalleled Instrument through Global Collaboration, ALMA Completely Changes our View of the Universe!

ALMA receivers developed at NAOJ. From left to right: Band 4 (millimeter wave, 125~163 GHz), Band 8 (submillimeter wave, 385~500 GHz), Band 10 (terahertz, 787~950 GHz). Credit: ALMA (ESO/NAOJ/NRAO)

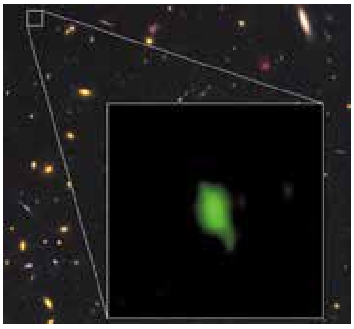
ALMA Science **03**

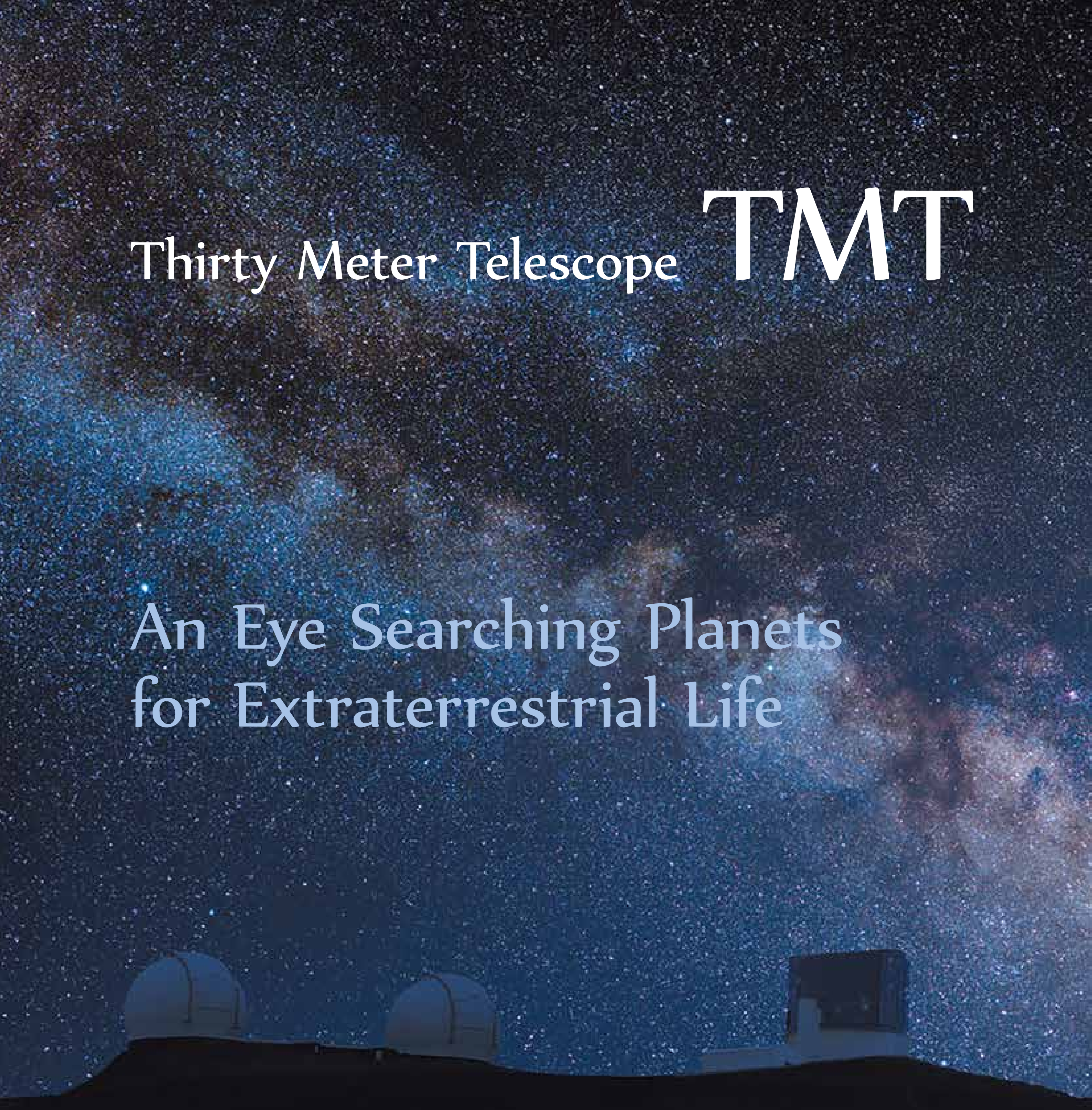
Searching for the Youngest Galaxies formed after the Big Bang

The Universe contains hundreds of billions of galaxies like our home Milky Way, each containing hundreds of billions of stars. When and how were these galaxies formed? How did they evolve? To solve this mystery we need to investigate distant galaxies over 10 billion light-years away; in other words, over 10 billion years back in time.

ALMA detected oxygen in the galaxy MACS1149-JD1 located 13.28 billion light-years from Earth. This is the record for the most distant (and therefore earliest) galaxy ever where oxygen has been detected. Oxygen didn't exist in the cosmos right after the Big Bang. It was produced by the nuclear reactions in the cores of stars and then scattered through space when those stars died. So if we can detect oxygen, it means that many stars must have already been born and died before that. From this discovery we learned that active star formation must have started about 250 million years after the Big Bang. ALMA has peered back into the era of galaxy formation in the earliest stages of the Universe.

The wavelengths of light reaching us from the distant Universe, in other words the early Universe, have been stretched by the expansion of space. The oxygen in the galaxy MACS1149-JD1 emitted infrared light; but by the time that light reached Earth it had been stretched to radio wavelengths, which can be observed by ALMA. Examining the way the wavelengths have been stretched allows us to accurately determine the distance to celestial objects.
Credit: ALMA (ESO/NAOJ/NRAO), NASA/ESA Hubble Space Telescope, W. Zheng (JHU), M. Postman (STScI), the CLASH Team, Hashimoto et al.



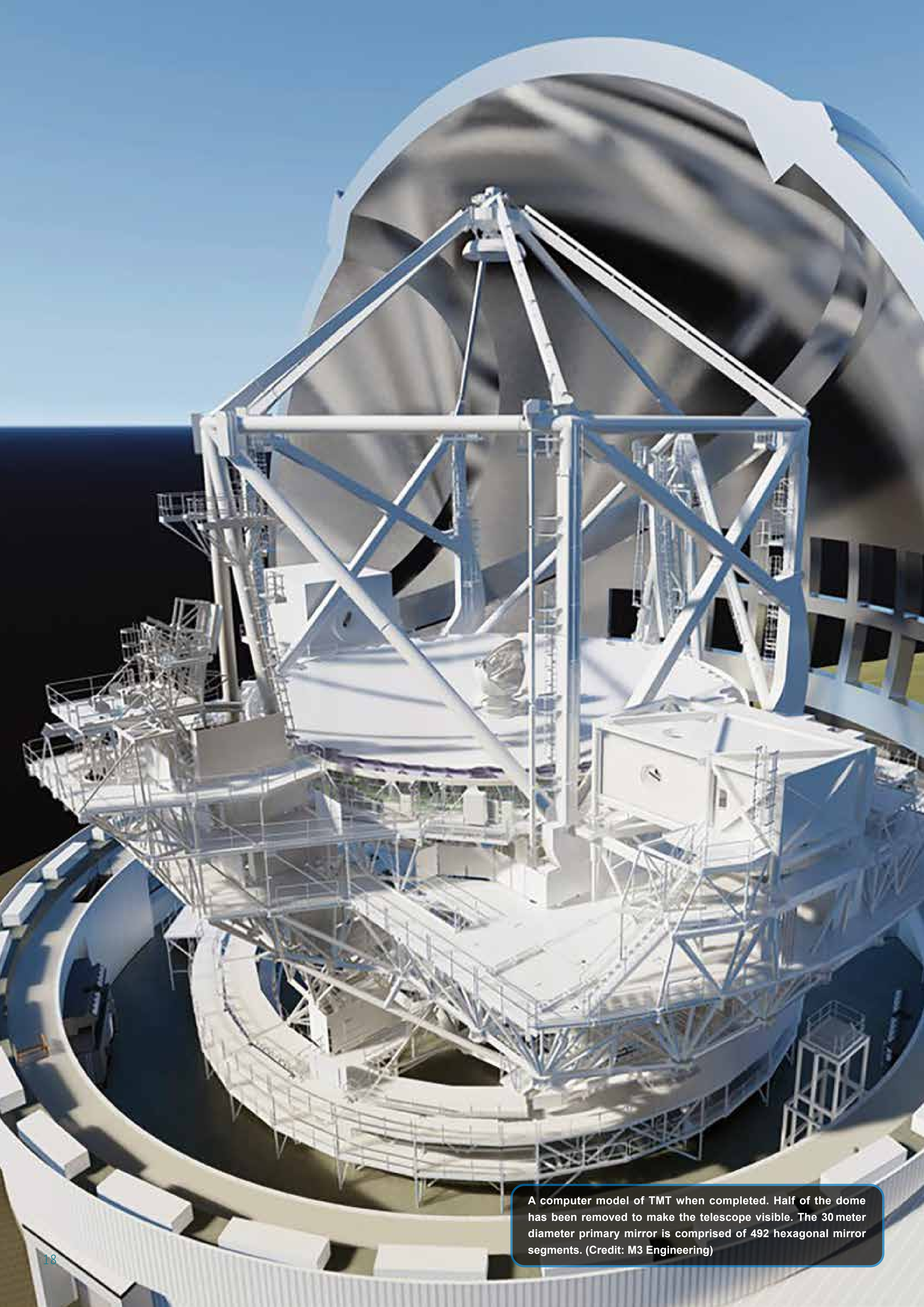


Thirty Meter Telescope TMT

An Eye Searching Planets for Extraterrestrial Life

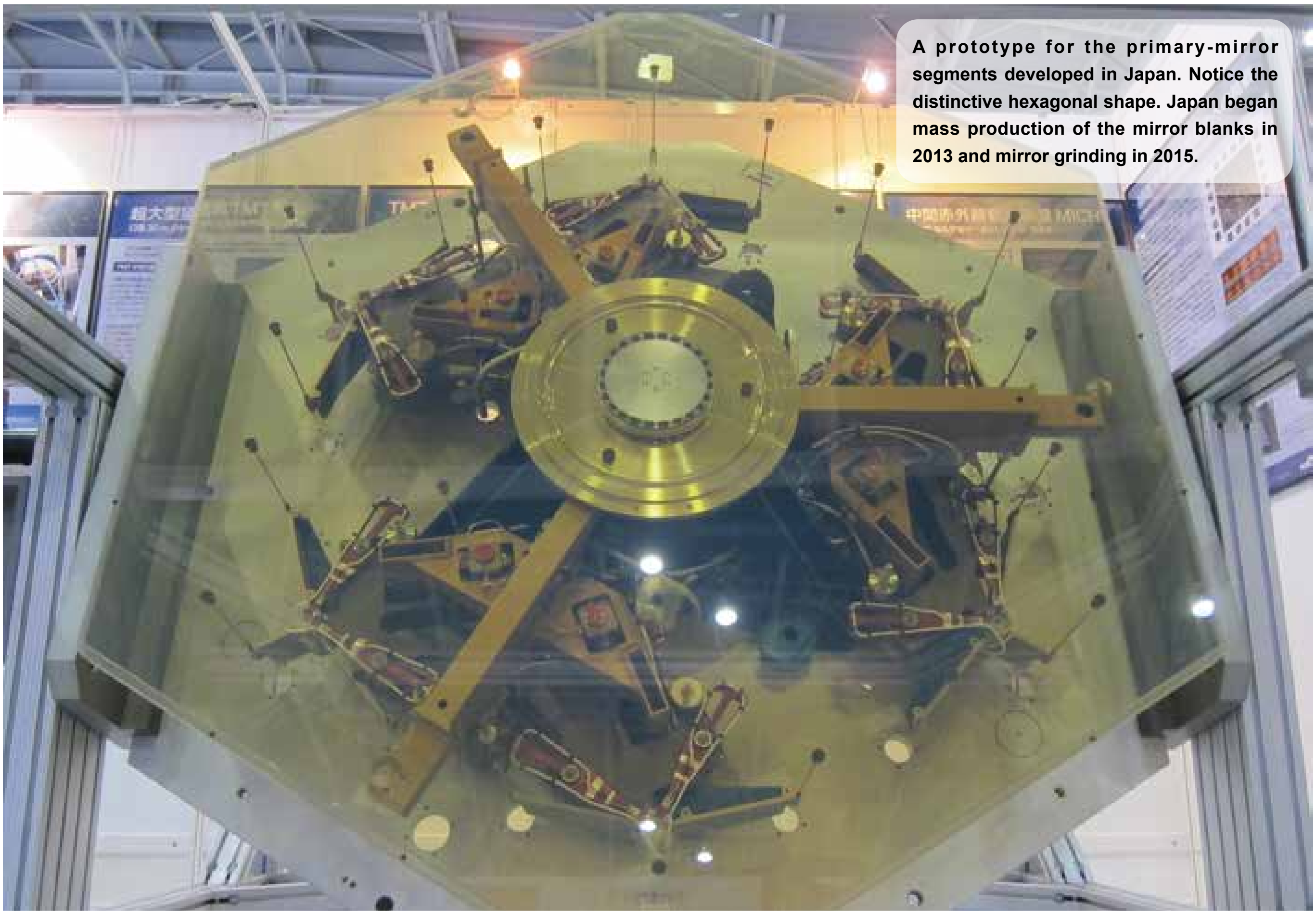
The Thirty Meter Telescope (TMT) is an optical-infrared telescope under construction in the summit region of Maunakea by a collaboration of five countries, Japan (represented by NAOJ), the United States, Canada, China, and India. With its 30 meter primary mirror, it will achieve high sensitivity and spatial resolution hitherto unknown to humans in the optical-infrared domain and search exo-planets for signs of life.

An Artist's Impression of TMT when completed on Maunakea. With its 30 meter diameter mirror, it will have over 10 times the light collecting power of the Subaru Telescope. With the aid of adaptive optics, in infrared observations it will achieve angular resolutions over 10 times better than the Hubble Space Telescope.



A computer model of TMT when completed. Half of the dome has been removed to make the telescope visible. The 30 meter diameter primary mirror is comprised of 492 hexagonal mirror segments. (Credit: M3 Engineering)

TMT Science 01



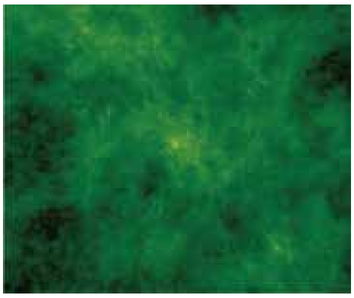
A prototype for the primary-mirror segments developed in Japan. Notice the distinctive hexagonal shape. Japan began mass production of the mirror blanks in 2013 and mirror grinding in 2015.

Searching for Planets with Earth-like Environments in Pursuit of Signs of Life

Numerous planetary systems have now been found in space, including ones resembling the Solar System, and ones harboring terrestrial planets. With 10 times the light gathering power of the current 8-meter class telescopes, TMT will undertake hitherto impossible observations of exo-planet systems. The ultimate goal is to find terrestrial planets in the habitable zone where the conditions are right for life, and look for evidence that life actually exists on them. Because terrestrial exo-planets are small and dim, existing telescopes can't image them directly. With its high sensitivity, TMT will capture the first image of a terrestrial exo-planet and enable spectroscopic analysis of the light reflected from the planet's surface.

For exo-planets with an orbit that passes in front of the parent star, as seen from the Earth, TMT will also be capable of spectroscopic analysis of light from the parent star that has passed through the atmosphere of the planet.

Through these observations TMT will definitively identify oxygen and organic molecules which indicate the existence of life.



A scene from a computer simulation depicting the birth of the first stars in the cosmos. Actually observing the light from these stars is one of the important science objectives of TMT.

Credit: Naoki Yoshida

TMT Science 02

Determining the Nature of the “First Objects” Born in the Universe

When and how were the first stars and galaxies in the Universe formed? This is one of the biggest questions in modern astronomy. ALMA and other telescopes have already found signs that the earliest stars formed in the first 200~300 million years after the Big Bang. But they haven't been able to capture the actual light from those stars. TMT with its impressive 30 meter aperture and high sensitivity aims to catch the light radiated by those first stars.

The first stars in the Universe were dazzling bright. When they died in supernova explosions, they ejected elements heavier than hydrogen and helium into their surroundings. In these ways they have had large influences on the following evolution of the Universe. TMT will catch the light from first-generation stars and accurately determine when they formed as well as how their radiation and supernova explosions affected the evolution of galaxies and the Universe.

A special glass with an extremely low thermal expansion rate is used for TMT’s primary mirror segments, which comprise part of Japan’s contribution. As of 2018, over 300 mirror blanks have been produced.

Credit: NAOJ/OHARA

TMT’s Giant Eye will Pierce the Deepest Mysteries of the Universe.

The distribution of galaxies based on data from the Sloan Digital Sky Survey, depicted using NAOJ’s Four-Dimensional Digital Universe viewer “Mitaka.” The true nature of dark energy which drives the expansion of the Universe is one of the important science objectives of TMT.

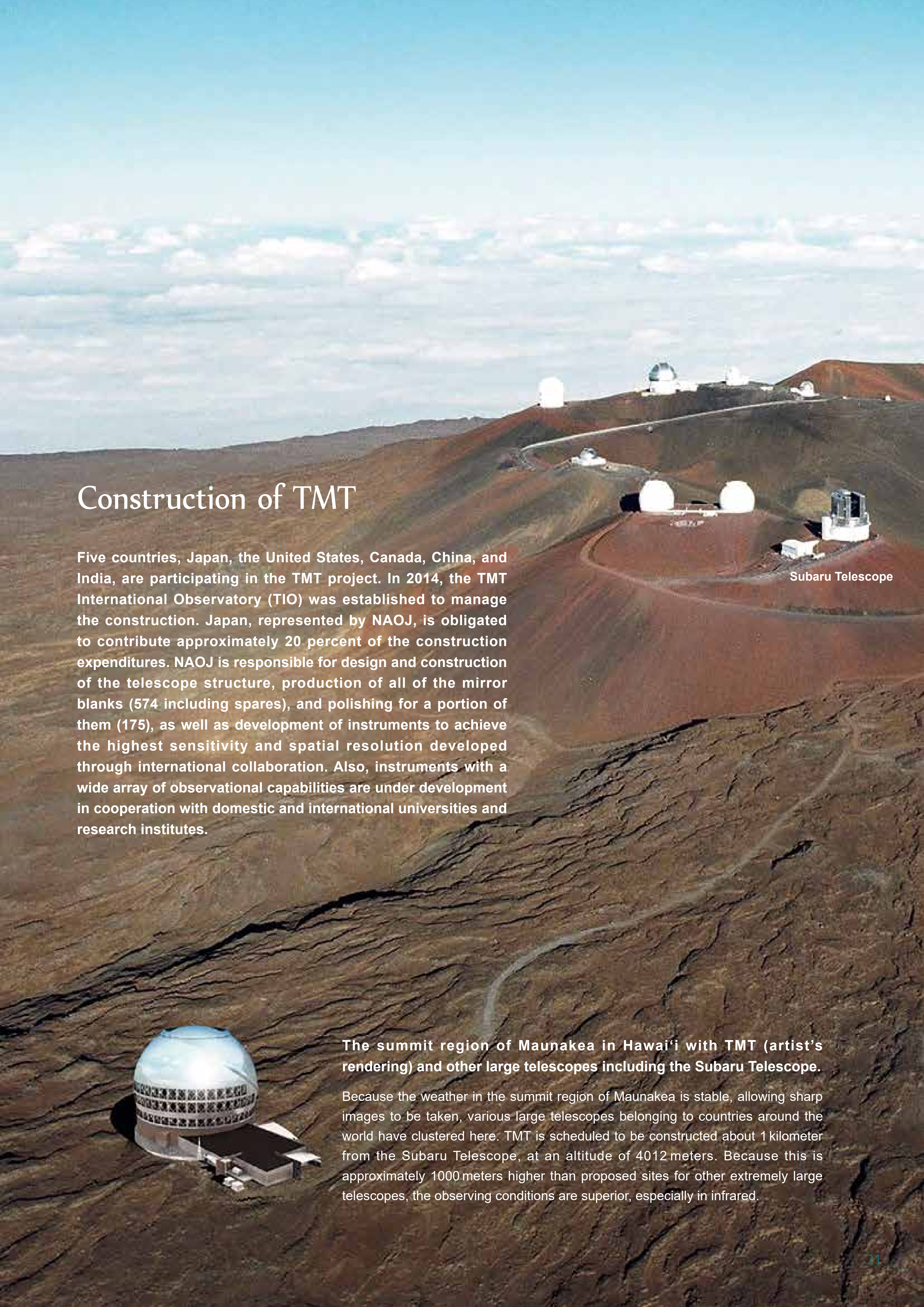
Credit: Tsunehiko Kato, ARC & SDSS, 4D2U Project, NAOJ

TMT Science 03

Directly Measuring Dark Energy’s Effect on the Expansion of the Universe

Recent observations have revealed that the expansion of the Universe is accelerating. Dark energy is the hypothesized energy acting as the “repulsive force” to explain this accelerating expansion. But its true nature is totally unknown and one of the largest mysteries in modern physics.

To solve the mysteries of dark energy we need to measure how the expansion of the Universe has changed over time and learn the characteristics of dark energy. By measuring the redshifts of many far away galaxies at different distances at some interval, for example 10 years, we can accurately measure how much the expansion of the Universe has accelerated (or decelerated) over that time. TMT’s high light collecting power will enable these kinds of high accuracy observations. We expect TMT to provide clues to understanding the true nature of dark matter.



Construction of TMT

Five countries, Japan, the United States, Canada, China, and India, are participating in the TMT project. In 2014, the TMT International Observatory (TIO) was established to manage the construction. Japan, represented by NAOJ, is obligated to contribute approximately 20 percent of the construction expenditures. NAOJ is responsible for design and construction of the telescope structure, production of all of the mirror blanks (574 including spares), and polishing for a portion of them (175), as well as development of instruments to achieve the highest sensitivity and spatial resolution developed through international collaboration. Also, instruments with a wide array of observational capabilities are under development in cooperation with domestic and international universities and research institutes.

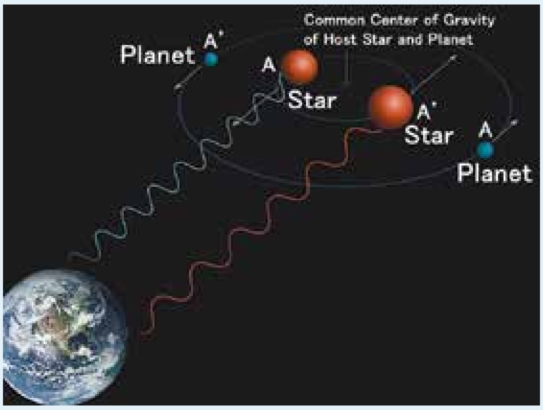
The summit region of Maunakea in Hawaiʻi with TMT (artist's rendering) and other large telescopes including the Subaru Telescope.

Because the weather in the summit region of Maunakea is stable, allowing sharp images to be taken, various large telescopes belonging to countries around the world have clustered here. TMT is scheduled to be constructed about 1 kilometer from the Subaru Telescope, at an altitude of 4012 meters. Because this is approximately 1000 meters higher than proposed sites for other extremely large telescopes, the observing conditions are superior, especially in infrared.

Uniting the Power of Subaru Telescope, ALMA, and TMT

① The Search for Life

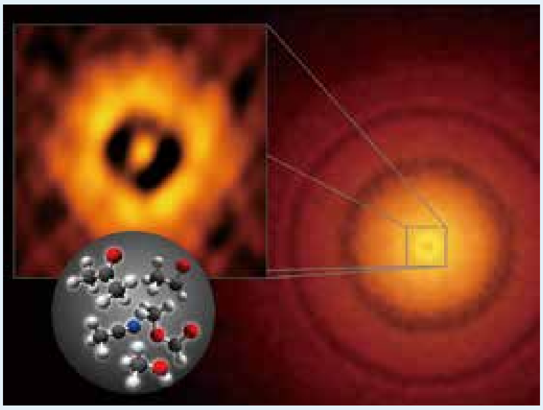
Detailed observations of the increasing number of exo-planets and protoplanetary disks, and searching for life in the Universe are the largest goals for 21st century astronomy. Together the Subaru Telescope, ALMA, and TMT form a winning team in the "search for life."



Finding Habitable Exo-Planets

The Subaru Telescope searches for exo-planets with masses similar to Earth through high precision spectroscopy to detect the wobble in the host star induced by the orbital motion of the planet.

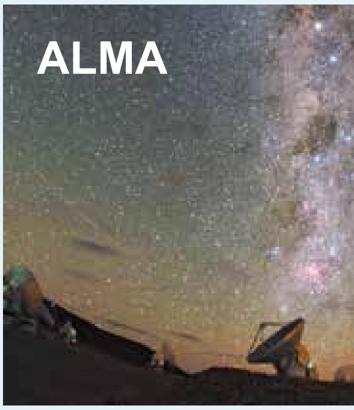
The host star moves in reaction to the planet's orbital motion. Planets can be detected indirectly via spectroscopic observations of the Doppler effect produced in the light from the host star.

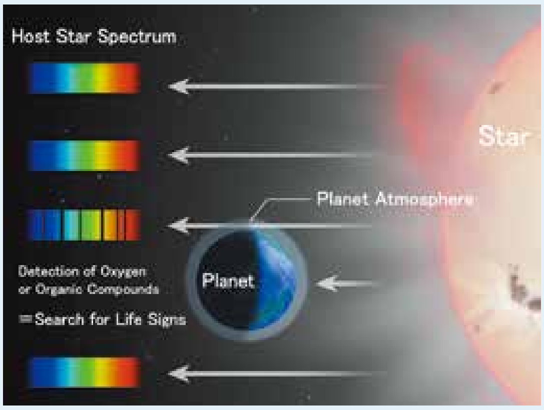


Finding Building Blocks for Life

ALMA devotes its energies to observations of formation sites of planets, the cradles of life, and searches for organic molecules which provide the building blocks for life.

The protoplanetary disk around the young star TW Hydrae photographed by ALMA. The radius of a gap near the central star (inset zoom-in) is comparable to Earth's orbit. ALMA detects the radio waves from various molecules in this kind of planet formation site. ★01





Finding Life Signs

TMT will target exo-planets discovered by the Subaru Telescope for detailed investigations of the planets' atmospheres through very high accuracy spectroscopic observations to try to find signs of life. This combined with ALMA's findings about the materials for life found in protoplanetary disks will bring us closer to understanding life in the Universe.

If oxygen or an organic compound is found through spectroscopic observations of the atmospheres of exo-planets, the odds are high that life exists there.

Credit: ★01 S. Andrews (Harvard-Smithsonian CfA) , ALMA (ESO/NAOJ/NRAO) ★02 ALMA (ESO/NAOJ/NRAO), NASA/ESA Hubble Space Telescope, W. Zheng (JHU), M. Postman (STScI), the CLASH Team, Hashimoto et al.

❸ Unveiling the mysteries of Dark Matter and Dark Energy

The Subaru Telescope, ALMA, and TMT each boast world leading performance in their respective fields. When their power is combined on common science themes, their capabilities to produce exciting discoveries and revolutionize our understanding of the Universe become even higher. NAOJ will operate these three telescopes organically and efficiently aiming for long term goals. Here let's examine three concrete examples of collaboration themes.

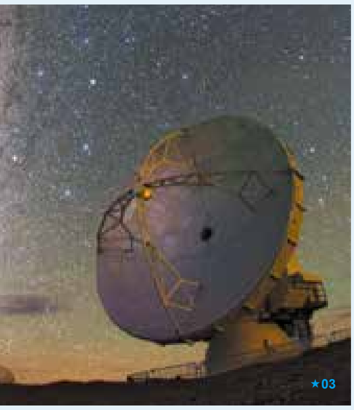
② The Search for the First Stars

One of the biggest problems in modern astronomy is peering into the farthest corners of space to determine the true nature of the first stars formed in the earliest Universe. The combination of the Subaru Telescope, ALMA, and TMT provides positive momentum to achieve this goal.

Search for Very Distant Objects

By searching for very distant objects in survey observations by the Subaru Telescope's ultra-wide-field-of-view Hyper Suprime-Cam, we can find targets for detailed follow-up observations using ALMA or TMT.

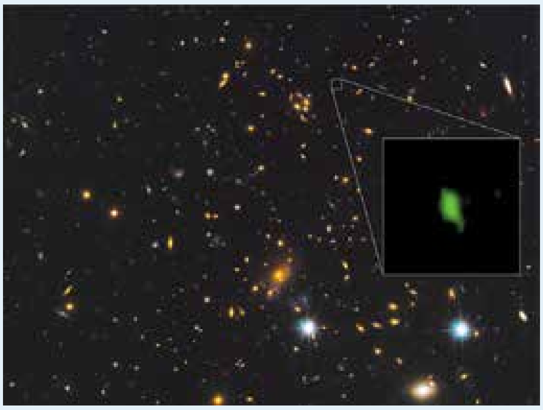
Countless galaxies in the distant Universe photographed by Hyper Suprime-Cam on the Subaru Telescope. The Prime Focus Spectrograph currently under development will accurately determine their distances.



Determining Chemical Composition

ALMA conducts high sensitivity follow-up observations of very distant object candidates discovered by the Subaru Telescope, catching radio waves emitted by the atoms contained in those objects to determine their chemical composition. This provides clues about the evolution of the earliest galaxies in the Universe.

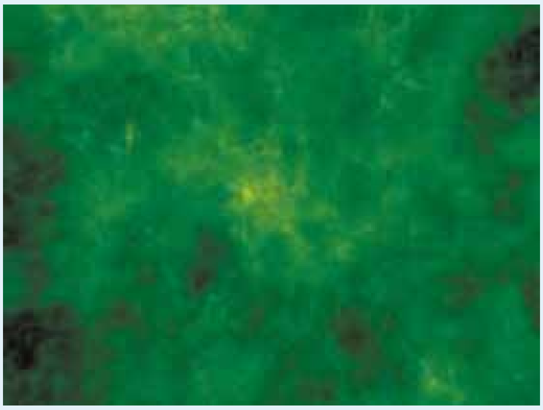
ALMA false color image (green zoom-in inset) showing the oxygen in the galaxy MACS 1149-JD1 located 13.28 billion light-years from Earth. ★02



Finding the First Stars

TMT will conduct high sensitivity follow-up observations of very distant object candidates observed by the Subaru Telescope, detecting the characteristic light emitted by helium atoms to elucidate when the first generation of stars formed and what their characteristics were.

A scene from a computer simulation depicting the birth of the first stars in the Universe. Verifying the results of theoretical studies of the first stars through observations is another important theme. ★04



★03 ESO/B. Tafreshi (twanight.org) ★04 Naoki Yoshida

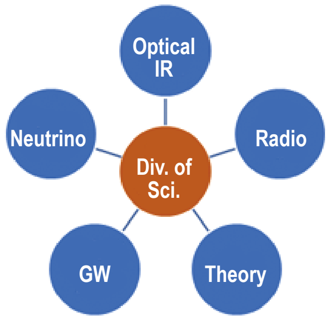
Despite the fact that dark matter and dark energy play critical roles in the formation of celestial objects and the accelerating expansion of the Universe, their true natures remain a mystery. The Subaru Telescope elucidates the 3D distribution of dark matter over wide areas through observations of gravitational lensing based on ultra-wide-field images. In contrast, ALMA uses its high resolution to measure the rotation speeds of individual galaxies and determine the dark matter distribution within a galaxy. By combining these we can determine the characteristics of dark matter spanning a wide scale from tens of thousands of light-years to billions of light-years. As for dark energy, investigating the distribution of dark matter found by the Subaru Telescope will elucidate the role of dark energy in the expansion of the Universe. In contrast, TMT will provide clues to the nature of dark energy by directly measuring the change in the expansion rate of the Universe.

Division of Science

NAOJ advances astronomy research utilizing leading-edge observational facilities like the Subaru Telescope, ALMA, and TMT. The NAOJ Division of Science is the driving force behind that research.

The NAOJ Division of Science is a new research unit established in April 2019. Since it is independent of other projects, researchers in the Division of Science can focus on their astronomy research without needing to manage the telescope operations.

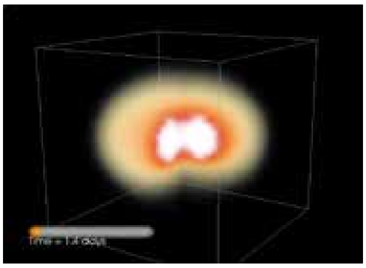
Under the keywords “fusion of theory and observation”, “multi-wavelength astronomy”, and “multi-messenger astronomy”, members of the Division of Science conduct research to advance modern astronomy based on their own original ideas, unimpeded by the traditional divisions between observation wavelengths or research methods. As part of these activities, we promote an organic fusion between the multi-wavelength observational facilities of NAOJ and simulation research using supercomputers. Other important missions include contributing to plans for future NAOJ activities based on a broad perspective on astronomy, and cultivating young researchers through training programs including postgraduate education. Through these efforts, we aim to attract young researchers from both inside and outside of Japan and make NAOJ a global hub for astronomy research.



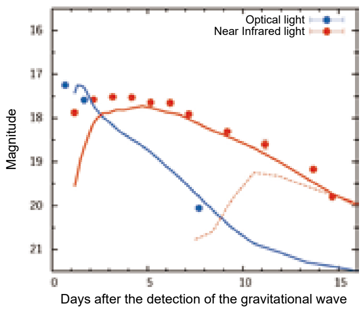
A diagram of the Division of Science's goal of unified astronomy utilizing various techniques.

Examples Combining Theoretical and Observational Research

Searching for the Cosmic Origins of Gold and Rare-Earth Metals

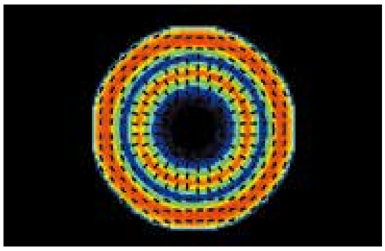


Credit: Masaomi Tanaka

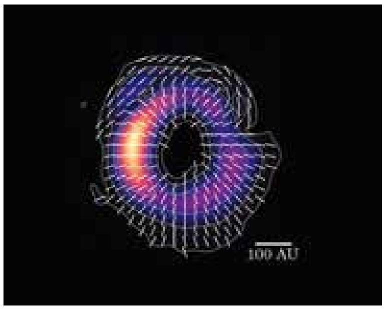


The origin of gold and rare-earth metals in the Universe had been a longstanding mystery, but we now know that they are produced in “neutron star mergers.” A neutron star is the object that remains after a massive star finishes its life in a supernova. Theoretical research and simulation studies using NAOJ’s supercomputer “ATERUI” predicted the explosion caused by a collision of two neutron stars (upper image) and the brightness variations expected in the formation of heavy elements after the explosion. Comparing these predictions to the brightness variations observed by the Subaru Telescope and other telescopes (lower graph) revealed evidence that elements including rare-earth metals were in-fact produced.

Measuring the Size of Planetary Seeds



Credit: Kataoka et al. (2015) ApJ 809.



Credit: ALMA (ESO/ NAOJ/NRAO), Kataoka et al.

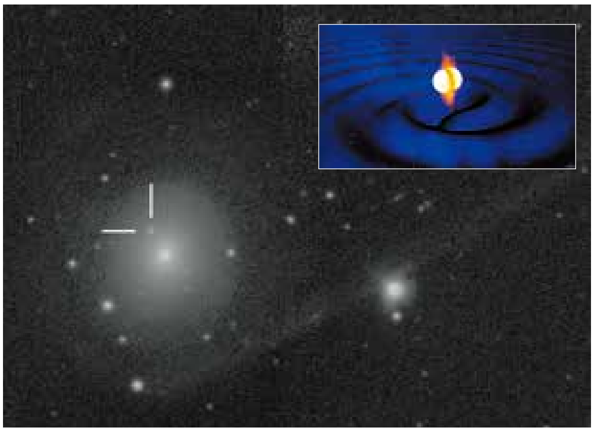
The theoretical prediction of the polarization of radio emission from a protoplanetary disk (upper image, black bars indicate the direction of the polarization, image color indicates the degree of polarized emission) and the polarized radio emissions from the protoplanetary disk around the young star HD142527 observed by ALMA (lower image, white bars indicate the direction of the polarization, image color indicates the strength of polarized emission). Comparing the polarization orientations obtained from observations to theoretical models allowed us to extract information about the sizes of the dust grains which become the material for planets.

Pursuing Multi-messenger Astronomy

Multi-messenger astronomy has started, using not only the optical, infrared, or radio waves observed by the Subaru Telescope or ALMA, but also gravitational waves and other signals to reveal multiple facets of the Universe.

Until the first half of the 20th century, humanity's observations of the heavens were limited to visible light. Entering the latter half of the century “multi-wavelength” astronomy utilizing radio waves, X-rays, infrared, and ultraviolet light revolutionized our understanding of the Universe.

Now, additional information has been added by signals other than electromagnetic waves, such as neutrino and gravitational waves. In 2017, the American LIGO detector captured the gravitational waves from the merger of two neutron stars for the first time in history. Comparing the subsequent optical observations conducted by the Subaru Telescope and other telescopes to theoretical predictions elucidated the origins of gold and rare-earth metals like platinum for the first time, throwing open the gates of multi-messenger astronomy. With the addition of the Large-scale Cryogenic Gravitational Wave Telescope KAGRA in the near future, further leaps are expected.



The photo of the gravitational wave source GW170817 taken by HSC on the Subaru Telescope and a visualization of the gravitational waves produced by a neutron star merger (upper right inset).

KAGRA’s vacuum duct (right). In the heart of KAGRA we find large-scale optical suspension systems developed at NAOJ. The mirror is covered by the red protective filter (center).

Collaboration with the Astrobiology Center

We pursue close cooperation with the Astrobiology Center (ABC) established by NAOJ’s parent organization NINS (National Institutes of Natural Sciences) as a new research institute.

The Astrobiology Center was established in 2015 to advance interdisciplinary studies of exo-planets and any life that may be hiding out in the Universe. It is a unique research institution that only NINS could create with its institutes encompassing both life sciences and astronomy. Fueled by recent major breakthroughs in exo-planet observations, it specializes in astrobiology, the scientific search for “life in the Universe.” ABC cultivates new research fields created from the fusion of various related fields such as astronomy and biology; engages in the search for planets outside of the Solar System and the search for life, both inside and outside of the Solar System; and develops the instruments for those searches. Having established the “study of life in the Universe” as an important research goal, cooperation between NAOJ and ABC will become increasingly important.

An example of oxygen-generating photosynthetic life (marimo). Research is continuing to determine how photosynthetic life affects the planet's atmosphere; what could be a “bio-signature”; and how can we best use TMT in this search?

In 2018, the near-infrared ultra-high precision Doppler shift detector developed with participation from ABC, NAOJ, and various universities was completed and conducted its first observations on the Subaru Telescope.

Technology Development

With its capability to develop cutting-edge observational facilities and instruments on its own, NAOJ provides strong support for leading edge research.

❶ Large Telescopes for Optical-Infrared and Radio

Starting with the Nobeyama 45-m Radio Telescope, followed by the Subaru Telescope, and ALMA, NAOJ has a history of developing large telescopes with world-leading performance. Based on this experience, NAOJ is now developing the 30 meter optical-infrared telescope TMT. TMT will control its giant 2500 ton telescope structure with a high precision better than a few ten-thousandths of a degree and capture images with a resolution of a few hundred-thousandths of a degree.

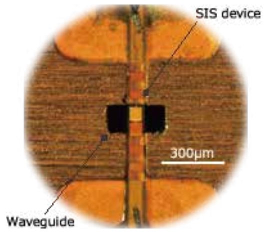
❷ High Accuracy Optical Space Telescope

In cooperation with industry, we developed a space telescope with humanity's highest angular resolution for solar observations and had it installed on JAXA ISAS's “Hinode” satellite. In order to achieve diffraction limited performance, we developed advanced technologies including a design which lets out unnecessary sunlight, the primary mirror support structure, low expansion materials, and a tip-tilt mechanism to prevent image deterioration due to minute vibrations in the satellite.

Solar Observing Satellite “Hinode”

❸ Optical and Radio Sensors

We develop high sensitivity detectors to observe the weak light and radio waves from space. In cooperation with industry we developed a CCD with a thicker silicon layer, vastly increasing its sensitivity to red light. We then installed 116 of the CCDs in Hyper Suprime-Cam on the Subaru Telescope and for the first time produced a wide-field 3D map of dark matter.

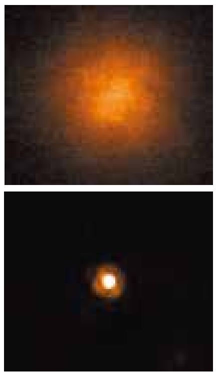


Superconducting device for ALMA’s highest frequency receiver.

NAOJ has specialized cleanroom equipment for developing superconducting devices and has realized steady production of superconducting components with world-leading performance. Here, we produced ALMA receivers including its highest frequency band (950 GHz). There are only a few facilities in the world that can produce these kinds of superconducting devices and receiver systems.

❹ Adaptive Optics to Correct for Atmospheric Distortion

When we observe heavenly bodies from the ground, fluctuations in Earth’s atmosphere cause the image to blur. Adaptive Optics is a technology which greatly improves the angular resolution of a ground-based telescope by correcting for the atmospheric fluctuations. NAOJ developed the adaptive optics system for the Subaru Telescope, successfully improving the angular resolution by a factor of 10 thus far, enabling the discovery of new exo-planets. This same technology can be used to observe the Earth from orbit or to observe living cells with a microscope.



Images of the same star taken without adaptive optics (above) and with adaptive optics (below).

❺ Photonic Techniques

The photonic technique to produce terahertz frequency radio waves from an optical laser.

We are developing the technology to control laser light to produce optical signals from low frequencies to terahertz frequencies, with the aim of improving radio telescopes. By using photonic techniques to combine optical and radio we have successfully generated a stable reference signal up to the terahertz band.

In this way, NAOJ is developing a variety of technologies for use in astronomy. We accumulate the knowhow to optimize the overall capabilities of the observational facilities by combining these techniques. There are no other examples of these kinds of activities at Japanese research institutes.

NAOJ Technology Patents

Because astronomy observations require techniques spanning a wide range of light and radio wavelengths, we can expect new applications improving the standard of living. NAOJ makes efforts to acquire patents for new technologies developed here. Through those patents, we aim to increase Japan’s presence in the competitive arena of astronomy and related fields while also generating patent revenue.

Patents held by NAOJ: 22 domestic, 11 overseas

Notable Patents ①

Adaptive Optics Systems and Optics Equipment, Patent No. 6394850 (patented in Japan and the United States)

A system for improving the accuracy of adaptive optics which compensate for fluctuations in the atmosphere, also capable of correcting for the distortion in images taken with microscopes to enable hitherto impossibly sharp images, with possible applications in precision measurement and life sciences.

Notable Patents ②

Optical Transmission Systems and Transmission Methods, Patent No. 5291143 (patented in Japan and the United States)

A technique to transmit signals across long distances by injecting a wide range of signal frequencies from low frequencies to terahertz frequencies into optical fibers, achieving a signal stability better than one second over 300,000 years.

Future Plans

NAOJ plans to maintain its strong leadership position in world astronomy. Together with the Japanese and worldwide research communities, we will open new doors in astronomy and plan next generation observational instruments.

What mysteries of the cosmos is astronomy poised to answer in the 2020s and 2030s? What role should the Japanese astronomy community play internationally? NAOJ is crafting long term plans to greatly advance the level of world astronomy based on a dialog with the astronomy communities inside and outside of Japan.

“Small Project” and “Investigation Group” activities are underway at NAOJ to form the foundation for concrete future plans.

“Small Projects” are projects which have already entered the development phase, including the “JASMINE Project Office”, “RISE Project Office”, “SOLAR-C Project Office” (refer to page 29), the “Subaru Prime Focus Spectrograph Project”, and “Subaru Ground Layer Adaptive Optics (GLAO) Project.”

“Investigation Groups” are groups planning large projects which will carry forward future astronomy or groups considering participation in large international projects. In April 2019, two Investigation Groups were established; the ngVLA (Next Generation Very Large Array) Group and the SKA1 (Square Kilometer Array 1) Group. The ngVLA plan led by the United States will create a large-scale centimeter/millimeter-wave interferometer. SKA1, advancing through cooperation with various countries, will construct large-scale, low-frequency interferometers in Australia and South Africa.

Subaru Prime Focus Spectrograph Project

These actuators for PFS, designed to position optical fibers at the desired targets, were developed at the Jet Propulsion Laboratory and California Institute of Technology. By accurately pointing each optical fiber at a different celestial object, the light from many objects can be fed into the spectrograph at one time.

We aim to develop a new spectrograph to be installed on the Subaru Telescope. By utilizing the Subaru Telescope’s superior light collecting power and wide field of view, PFS will allow simultaneous spectral observation of up to 2400 celestial objects across a wide field of view of 1.3-degree diameter. Compared to current optical spectroscopy, PFS is expected to offer a 50-fold increase in field of view and 20-fold increase in the number of targets in each observation. By using PFS to disperse the light from many distant galaxies at the same time, we can measure the distances to the galaxies very efficiently. PFS is being developed through international collaboration among 12 institutions from 7 countries and regions led by Kavli Institute for the Physics and Mathematics of the Universe. NAOJ is to play a major role in the installation and operation of the instrument.

Subaru Ground Layer Adaptive Optics (GLAO) Project

By directing four laser beams into the sky and making the upper atmosphere glow, wide-field adaptive optics create artificial stars (laser guide stars), which enable us to measure and compensate for the blurring by Earth’s atmosphere. (Conceptual Image)

We aim to carry out an extensive upgrade of the Subaru Telescope to keep the telescope on the cutting edge of astronomy. By using multiple laser guide stars and wavefront sensors, GLAO compensates for the blurring effect of the atmosphere across wide areas of the sky in real time and allows us to conduct observations with unprecedented depth and field of view, and with an image sharpness comparable to the Hubble Space Telescope. As part of the upgrade process, a deformable secondary mirror is to be installed on the Subaru Telescope. It will provide a sharp field of view of up to 20 arcminutes in diameter and, in infrared observations, a resolution of about 0.2 arcseconds.

Various Projects and Centers Supporting NAOJ's Extensive Astronomy Research

NAOJ has various projects and centers to conduct and support a wide range of astronomy research.

Gravitational Wave Project Office

The KAGRA vacuum duct.

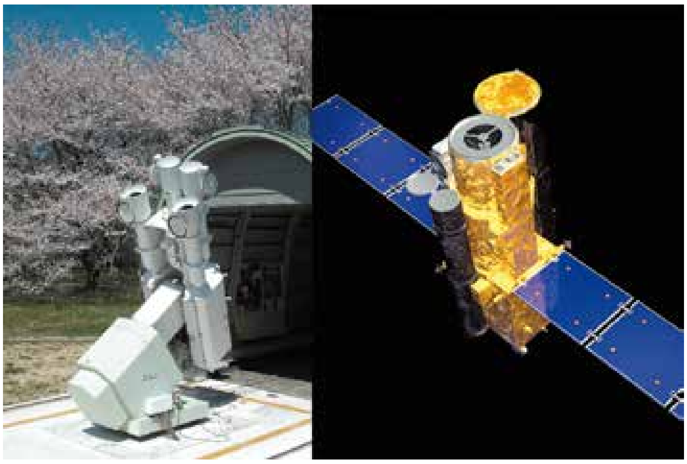
The first detection of gravitational waves by LIGO marked the beginning of gravitational-wave astronomy. In collaboration with ICRR, KEK, and other institutes, we conduct the KAGRA project; a large interferometer with 3-km L-shaped arms in an underground tunnel at Kamioka Mine. KAGRA was designed based on TAMA300, a 300-m laser interferometer situated underground in NAOJ Mitaka Campus. TAMA300 is now used to develop new technologies for upgrading KAGRA and conduct pre-installation testing of the instruments for KAGRA. The project office also conducts research on improving the sensitivity of gravitational-wave detectors and the possibility of a space-based gravitational-wave observatory.

Center for Computational Astrophysics (CfCA)

ATERUI II

We promote the use of computer systems for simulation including ATERUI II; the world's fastest supercomputer for astrophysics (theoretical peak performance of 3 Pflops), research and development for simulation technology; and astronomy research using simulations. Our objective is to reveal aspects of the Universe that cannot be observed by any telescope through calculations based on the laws of physics. The project office has made many contributions to our understanding of the large-scale structure of the Universe, and the formation and evolution of celestial objects. We strive to provide more realistic simulations and address the unsolved mysteries of the Universe.

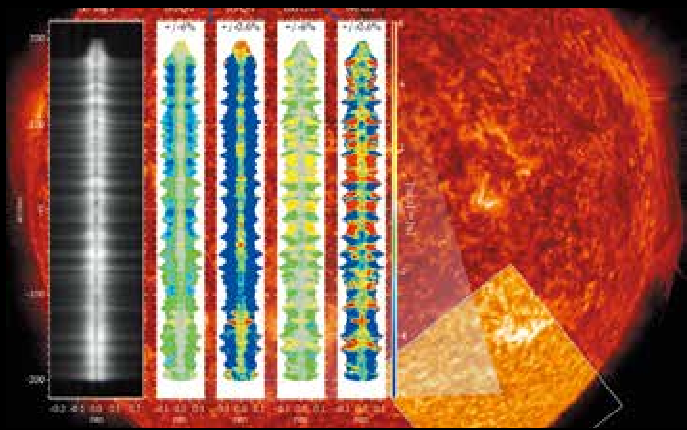
Solar Science Observatory



The Solar Flare Telescope (left) and the Solar Observing Satellite HINODE (right).

Using the solar telescopes in Mitaka and observation satellites including “Hinode,” we conduct research on solar magnetic phenomena such as the generation-annihilation processes of the solar magnetic field; heating in the chromosphere and corona; and flares. At the same time, we open our data to the public. Our research subjects include: regularity of magnetic helicity which provides clues to the generation of the solar magnetic field occurring inside the Sun; magnetic waves propagating through chromospheric/coronal jets and prominences; velocity fields in the footpoints of coronal loops which could act as predictors of nanoflares; intense jets inside and around sunspots; and quantitative evaluation of the magnetic flux in solar active regions. We aim to further improve the resolution and precision of magnetic observations and, while promoting a quantitative understanding of solar magnetic phenomena, to understand magnetic phenomena that occur naturally in the Universe.

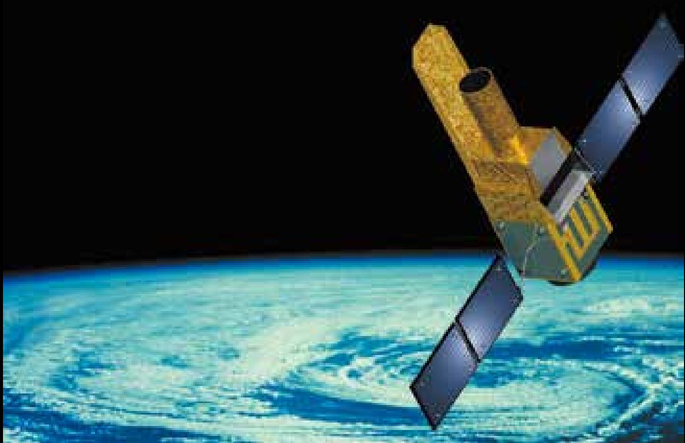
SOLAR-C Project Office



The polarized spectrum of the solar Lyman-alpha line obtained for the first time in the world by CLASP.

The “Hinode” satellite discovered that the solar photosphere, chromosphere, and corona are filled with unexpected dynamic phenomena such as tiny jets and waves. To measure the magnetic field in the chromosphere, NAOJ conducted the sounding rocket experiments, CLASP-1 and CLASP-2, together with NASA, and contributed to their success by developing an ultraviolet telescope and a polarization spectrometer. In addition, we are developing the Sunrise Chromospheric Infrared spectroPolarimeter (SCIP) for the SUNRISE-3 Balloon-Borne Solar Observatory of the Max Planck Institute. In the subsequent SOLAR-C project, we plan to conduct ultraviolet spectroscopic observations of the chromosphere and corona at higher spatial resolution than that of Hinode, and measure the movement of gas and the fluctuations in the density of gas. Through these efforts, we hope to elucidate the origin of the chromosphere and corona, and the mechanism of flare explosions.

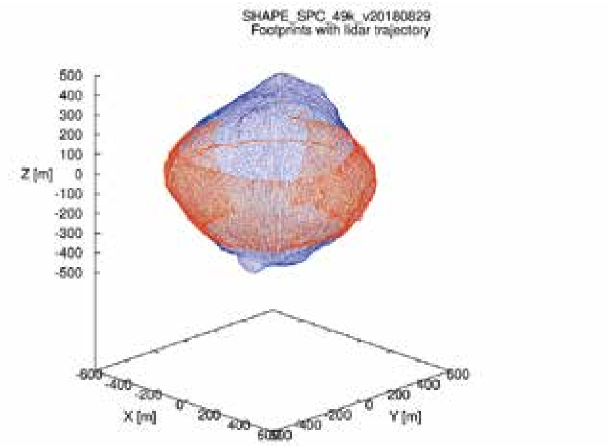
JASMINE Project Office



Small-JASMINE

JASMINE is a satellite for measuring the distances and apparent motions of stars around the central bulge of the Milky Way with unprecedented precision. We have already built a very small satellite, Nano-JASMINE, and now aim to develop Small-JASMINE as a part of the M-class missions of JAXA. The objective of the Small-JASMINE mission is to perform Galactic Center Archaeology through the creation of a 5 dimensional data catalog (including stellar positions on the celestial sphere, annual parallaxes, and proper motions) and the exploration of the nuclear bulge to understand the structure of the Milky Way Galaxy and the evolution of its supermassive black hole. By observing dips in starlight caused by planets passing in front of their host stars, we also aim to investigate Earth-like planets, particularly those located in the habitable zones around low-temperature stars.

RISE Project Office



The shape of Ryugu observed by the Hayabusa2 laser altimeter.★

Investigating the inner structure of the objects in our Solar System, we aim to understand their evolution and origin. In the SELENE Project led by JAXA, we obtained accurate gravity field data for the opposite side of the Moon and revealed the terrain features of the Moon including its polar regions. We are now conducting research on not only the Moon, but also Mercury, Mars, the Jovian system, and the asteroids. In JAXA’s Hayabusa2 Project, we developed a laser altimeter in cooperation with researchers both inside and outside of Japan and are responsible for its operation and scientific observations. For future missions, we are developing the Ganymede Laser Altimeter (GALA) to be installed on the Jupiter Icy Moons Explorer (JUICE) with international collaboration and participating in scientific discussions about MMX, Japan’s sample return mission to a Martian moon.

★Credit: NAOJ, JAXA, Chiba Institute of Technology, the University of Aizu, Nihon University, Osaka University.

Mizusawa VLBI Observatory

The 20-m radio telescope at Mizusawa VLBI.

VERA of Mizusawa VLBI Observatory is a project combining four 20-m radio telescopes located at Mizusawa, Iriki, Ogasawara, and Ishigakijima to create a huge virtual radio telescope with a diameter of 2300 km. VERA maps our Milky Way galaxy by measuring the distances to celestial objects with high accuracy. Aiming to improve the performance by adding radio telescopes, we promote international collaborations mainly with observatories in East Asia. We have built KaVA, a network combining VERA and three KVN radio telescopes located in South Korea, and we are establishing the East Asia VLBI Network by adding antennas in China.

Nobeyama Radio Observatory

The Nobeyama 45-m Radio Telescope.

The 45-m telescope at Nobeyama Radio Observatory pioneered millimeter-wave astronomy in Japan. Utilizing the high sensitivity, we observe radio waves emitted from various interstellar molecules. We have especially focused on wide-field observations of star-forming regions and the Milky Way, and detailed observations of molecular gas in nearby galaxies. We have obtained the most detailed radio map of the Milky Way and one of the largest collection of radio images of 147 galaxies. These data are accessibles to researchers around the world through the Virtual Observatory.

Astronomy Data Center

Computer array for astrophysical calculations.

The Astronomy Data Center provides comprehensive services related to the collection and disclosure of data collected by NAOJ and other domestic and overseas facilities. In addition to developing the analysis software for Hyper Suprime-Cam, we operate the Japanese Virtual Observatory (JVO) through which anyone can access observational data obtained by the Subaru Telescope and ALMA to promote database astronomy.

Advanced Technology Center

Mechanical Engineering Shop.

The development of new observation instruments has stimulated advances in astronomy. The Advanced Technology Center is a base for the development of advanced instrumentation for astronomy in wide ranges of wavelengths, both ground-based and space-based. We have developed Hyper Suprime-Cam (HSC) for the Subaru Telescope, receivers for ALMA, a visible-light telescope and an X-ray telescope for Hinode, and optical instruments for KAGRA. We also develop next-generation instruments including focal plane instruments for TMT and new receivers for ALMA.

Public Relations Center

We are committed to disseminating the latest findings in astronomy, publishing new astronomical object reports and the Ephemeris, and supporting the activity of the IAU Office for Astronomy Outreach. In addition, we play a major role in science communication activities for astronomy outreach through collaboration with public observatories, museums, and planetariums. We also operate the NAOJ Library which houses a number of valuable books related to astronomy.

Regular Stargazing Party using the 50-cm Telescope.

Organization

The Project System clarifies the activities and plans of NAOJ in terms of projects, centers, and divisions, each with specific goals and timelines. The Project System advances the sharing of resources throughout the entire observatory; defines the responsibilities and capabilities of project leaders and staff; and improves the clarity and independence of research.

- Advisory Committee for Research and Management
- Director General
  - Vice-Director General (on General Affairs)
  - Vice-Director General (on Program)
  - Director of Engineering
  - Director of Research Coordination
  - Executive Advisors to the Director General

Projects

C Projects

- Mizusawa VLBI (Very Long Baseline Interferometry) Observatory — SKA1 Group
- Nobeyama Radio Observatory
- Solar Science Observatory
- Subaru Telescope — Okayama Branch Office
- Center for Computational Astrophysics
- NAOJ Chile
- ALMA Project — ngLVA Group

B Projects

- Gravitational Wave Project Office — Kamioka Branch Office
- TMT (Thirty Meter Telescope)-J Project Office — California Office

A Projects

- JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration) Project
- RISE (Research of Interior Structure and Evolution of Solar System Bodies) Project
- SOLAR-C Project
- Subaru Prime Focus Spectrograph (PFS) project
- Subaru Ground Layer Adaptive Optics (GLAO) project

Centers

- Astronomy Data Center
- Advanced Technology Center
- Public Relations Center

Division of Science

- Collaborative Projects
  - Inter-university Collaboration: Optical and Infrared Synergetic Telescopes for Education and Research (OISTER)
  - Inter-university Collaboration: Japanese VLBI Network (JVN)

Administration Department

- General Affairs Division
- Research Promotion Division
- Financial Affairs Division
- Accounting Division
- Facilities Division

- Research Enhancement Strategy Office
  - Research Evaluation Support Office
- Office of International Relations
- Human Resources Planning Office
- Safety and Health Management Office
- Engineering Promotion Office
- IT Security Office

3 Groups of Projects and 3 Centers

At NAOJ, projects are divided into 3 groups based on their roles.

C Projects group - the seven projects such as Subaru Telescope, ALMA, the Supercomputer “ATERUI II,” Solar Observing Satellite HINODE, etc., which have been completed as NAOJ facilities and are operating. This project group is the main driving force of NAOJ, actively supporting leading edge observations and research.

B Projects group - two project offices that are under construction or being developed. The TMT-J Project Office is constructing the 30 meter telescope TMT. The Gravitational Wave Project Office is undertaking gravitational wave observations using KAGRA, the Large-scale Cryogenic Gravitational Wave Telescope.

A Projects group - projects pursuing small-scale development plans. In April 2019, the “Subaru Prime Focus Spectrograph Project” and the “Subaru Ground Layer Adaptive Optics Project” were added to the already existing “JASMINE Project Office”, “RISE Project Office”, and “Solar-C Project Office.”

“Investigation Groups” are established to investigate observational instrument development plans closely related to NAOJ’s future strategy. Currently the ngVLA Group and SKA1 Group are active.

An additional two, the OISTER Network of optical-infrared telescopes in Japan and Japanese VLBI Network are being pursued in cooperation with Japanese universities.

The three centers extend across the framework of individual projects and play key roles in equipment development, technological research, data analysis, data archiving, and public outreach activities. The centers provide the basic infrastructure of NAOJ.

NAOJ Facilities

Our research facilities have been set up around the world for better observational environments to explore the Universe.

Public Access to NAOJ facilities

To widely disseminate our research results to the public, the major facilities of NAOJ offer visitors' areas, annual open house days, or regular stargazing parties.

NAOJ Nobeyama

462-2, Nobeyama, Minamimakimura, Minamisaku, Nagano 384-1305, Japan
https://www.nro.nao.ac.jp/en/

Nobeyama Radio Observatory

Nobeyama Radio Observatory raised Japanese radio astronomy to the top tier internationally. The 45-m Radio Telescope is one of the largest millimeter wave radio telescopes in the world. It has produced numerous discoveries including new interstellar molecules and signs of a black hole.

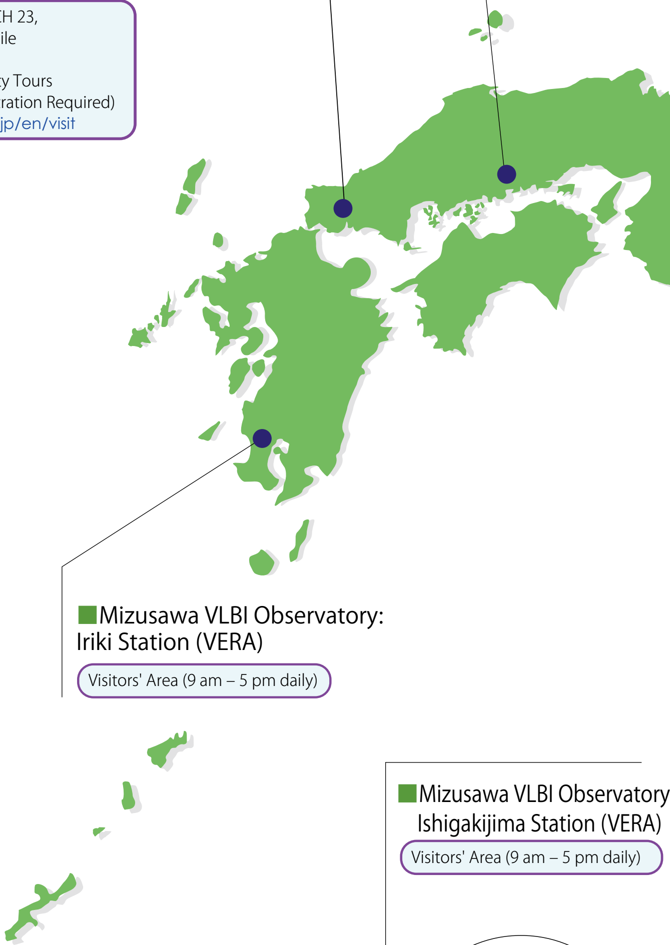
GWPO Kamioka Branch Office, KAGRA

KAGRA, a gravitational wave telescope in the Kamioka Mine, aims to expand the field of gravitational wave astronomy. The Kamioka Branch of the Gravitational Wave Project Office (GWPO) supports the installation and commissioning of KAGRA.

Subaru Telescope Okayama Branch Office

NAOJ is responsible for open-use observations at the 3.8 meter "Seimei" Telescope of Okayama Observatory, the Astronomical Observatory of the Graduate School of Science, Kyoto University. This provides domestic researchers with observing opportunities on the largest optical and near-infrared telescope in Japan.

Mizusawa VLBI Observatory: Yamaguchi Station



Mizusawa VLBI Observatory: Iriki Station (VERA)

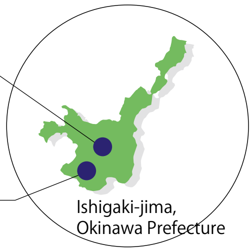
Visitors' Area (9 am – 5 pm daily)

Mizusawa VLBI Observatory: Ishigakijima Station (VERA)

Visitors' Area (9 am – 5 pm daily)

Ishigakijima Astronomical Observatory

Visitors' Area (10 am – 5 pm, Wednesday to Sunday, excluding New Year's season)
Star Parties (7 pm – 10 pm, Saturdays, Sundays, and holidays)



NAOJ Chile

NAOJ Chile, NAOJ ALMA Project

Alonso de Cordova 3788, Oficina 61B, Vitacura, Santiago, Chile
TEL +56-2-2656-9253
https://alma-telescope.jp/en/

The Atacama Desert in northern Chile, one of the driest places on Earth, is an ideal location for short wavelength radio wave (millimeter and submillimeter wave) observation. ALMA and ASTE have been established here. The NAOJ Chile office and the Joint ALMA Observatory Santiago Central Offices are located in Santiago, the capital of Chile.

ALMA Operations Support Facility

Kilometro 121, Carretera CH 23,
San Pedro de Atacama Chile
Public Visits
Operations Support Facility Tours
(Advanced Internet Registration Required)
https://alma-telescope.jp/en/visit

ALMA

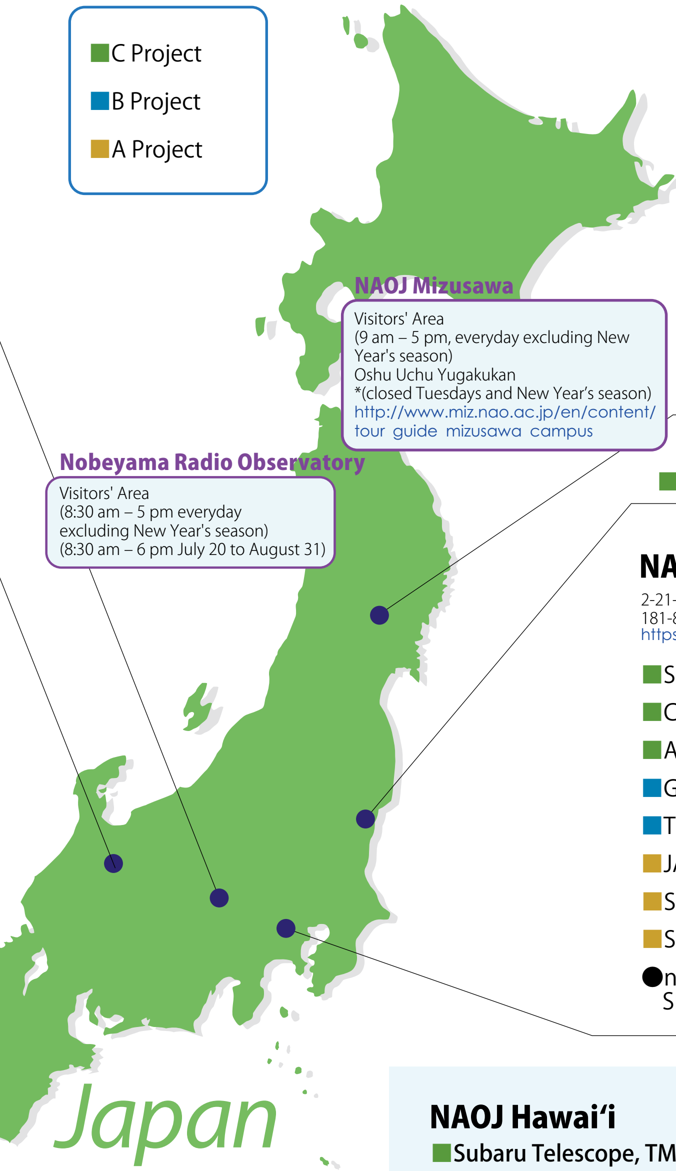
ALMA, led by NAOJ, the U.S. National Radio Astronomy Observatory, and European Southern Observatory with participation by Taiwan and South Korea, is a giant radio telescope array constructed on a 5000 meter elevation plateau in Chile. Full operation began in 2013. ALMA consists of 66 parabolic antennas, including 16 built by Japan.

ASTE

ASTE observes submillimeter radio waves with wavelengths shorter than 1 millimeter. Established in the Atacama Desert with optimal conditions for submillimeter astronomy, it applies its strength to observations of the southern sky including the Galactic center region, nearby star-forming regions, and distant galaxies.

ALMA Operations Support Facility

The Operations Support Facility is located 30 kilometers away from the ALMA Array Operations Site. It serves as the "base camp" for ALMA with lodgings and a cafeteria for ALMA staff in addition to the control room for remote operation of ALMA and laboratories where instrument maintenance is performed.



■C Project
■B Project
■A Project

NAOJ Mizusawa

Visitors' Area
(9 am – 5 pm, everyday excluding New Year's season)
Oshu Uchu Yugakukan
*(closed Tuesdays and New Year's season)
http://www.miz.nao.ac.jp/en/content/tour_guide_mizusawa_campus

Nobeyama Radio Observatory

Visitors' Area
(8:30 am – 5 pm everyday excluding New Year's season)
(8:30 am – 6 pm July 20 to August 31)

NAOJ Mizusawa

2-12, Hoshigaoka, Mizusawa, Oshu, Iwate 023-0861, Japan
http://www.miz.nao.ac.jp/en/

■Mizusawa VLBI Observatory (VERA)

This facility has a long history starting with the International Latitude Observatory. One of the VERA stations creating a 3D map of the Milky Way is located here.

■Center for Computational Astrophysics

NAOJ Mizusawa hosts ATERUI II, the world's fastest supercomputer dedicated to astronomy.

■RISE (Research of Interior Structure and Evolution of Solar System Bodies) Project

The first accurate gravity and topography maps of the Moon were obtained using the KAGUYA mission's laser altimeter, relay satellite, and VLBI satellite. We intend to develop our research further by promoting exploration of not only the Moon but also asteroids and the Jovian System.

■Mizusawa VLBI Observatory: Ibaraki Station

NAOJ Mitaka (Headquarters)

2-21-1 Osawa, Mitaka, Tokyo
181-8588, JAPAN
https://www.nao.ac.jp/en/

As the headquarters of NAOJ, Mitaka Campus houses the offices of various projects and divisions, as well as administrative offices.

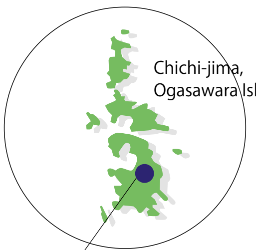
■Solar Science Observatory
■Center for Computational Astrophysics
■ALMA Project
■Gravitational Wave Project Office
■TMT-J Project Office
■JASMINE Project Office
■Subaru PFS Project Office
■Subaru GLAO Project Office
●ngVLA Investigation Group/ SKA1 Investigation Group
●OISTER Network/ Japanese Domestic VLBI Network
■Astronomy Data Center
■Advanced Technology Center
■Public Relations Center
■Division of Science
■Office of International Relations

NAOJ Mitaka

・Visitors' Area
(10 am – 5 pm, everyday excluding New Year's season)
・Annual Open House Day
October 25-26, 2019
・Regular Stargazing Parties/4D2U Dome Theater Screenings
(Both require reservations.)
https://www.nao.ac.jp/en/access/mitaka/visit/

NAOJ Subaru Telescope

Regular Tours
Summit Tour Program
https://www.subarutelescope.org/Information/Tour/Summit/index.html



■Mizusawa VLBI Observatory Ogawawara Station (VERA)

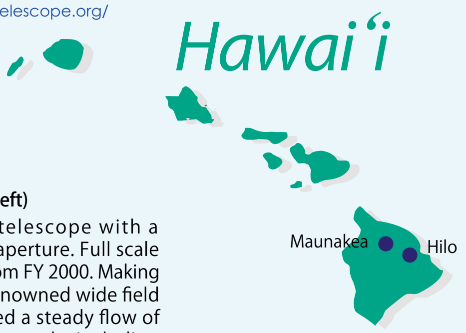
Visitors' Area (9 am - 5 pm daily)

NAOJ Hawai'i

Hilo Base Facility
650 North A'ohoku Place, Hilo, Hawai'i 96720 U.S.A.
TEL +1-808-934-7788
https://www.subarutelescope.org/

■Subaru Telescope, TMT-J Project Office

With many clear nights and stable airflow, the summit region of Maunakea (4200 meter altitude) is well suited for astronomy observations. Here, NAOJ constructed and operates the Subaru Telescope, and the 30 meter optical-infrared telescope TMT is being constructed through international collaboration.



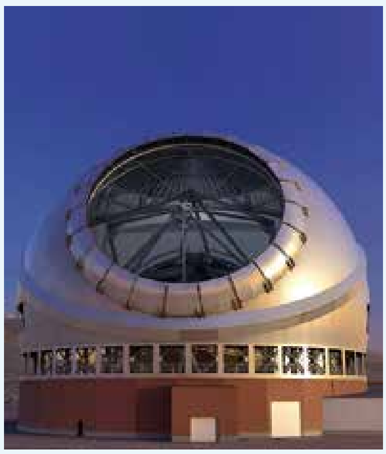
Hawai'i Island,
Hawai'i State,
United States of America

The Subaru Telescope (left)

An optical-infrared telescope with a world-class 8.2 meter aperture. Full scale observations started from FY 2000. Making best use of its world-renowned wide field of view, it has produced a steady flow of world-leading research results including the discovery of very distant galaxies.

TMT (right)

An extremely large optical-infrared telescope being constructed through international collaboration between Japan, the United States, Canada, China, and India. With more than 10 times the light collecting power of the Subaru Telescope, it aims to discover signs of life in the atmospheres of exo-planets and capture the light from the earliest stars in the Universe.



Hilo Base Facility (left)

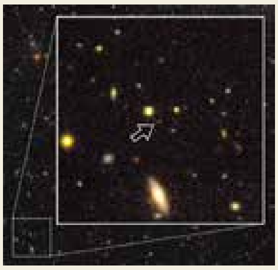
The base facility of Subaru Telescope is located in Hilo on Hawai'i Island. As the base for the unified operation of the Subaru Telescope and TMT, this facility has laboratories, a machine shop, computer room, a remote observation room, etc.

Top Level Research with NAOJ Facilities

NAOJ develops and operates large-scale research facilities that would be difficult for individual universities to maintain. By sharing these facilities with researchers from universities in Japan, NAOJ provides cutting-edge research environments to them. In addition to sharing facilities, NAOJ provides extensive user support to cultivate young researchers; helps individual researchers improve the quality of their research; promotes interdisciplinary research; and conducts collaborative research with researchers in Japan and abroad. Moreover, we disseminate our achievements to a worldwide audience via NAOJ press releases to return benefits to society, while at the same time contributing to improving the international presence of Japanese universities and other institutions.

We regularly hold Users' Meetings, in which we share the present state of our telescopes and their future plans to discuss how to yield better results.

Selected Results from the Subaru Telescope

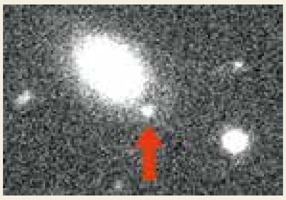


A supermassive black hole (red dot indicated by the arrow) located 13.05 billion light-years away.

Discovery of many supermassive black holes 13 billion light-years away.

A research team led by Yoshiki Matsuoka of Ehime University used Hyper Suprime-Cam (HSC) mounted on the Subaru Telescope and discovered 83 supermassive black holes 13 billion light-years away. The study showed that a large number of supermassive black holes already existed in the very early phase of the Universe.

Astronomers capture a supernova within a day after the explosion.



A supernova (indicated the arrow) soon after the explosion captured by the Subaru Telescope.
Credit: The University of Tokyo/NAOJ

A research team led by Ji-an Jiang of the University of Tokyo found a supernova within a day after explosion using the Subaru Telescope.Comparisons of the observation results and theoretical predictions suggest that helium accreted onto a white dwarf (burned-out core of a star) igniting nuclear fusion, which triggered the subsequent explosion of the whole star.

The Andromeda Galaxy photographed by Hyper Suprime-Cam on the Subaru Telescope.

Dark matter is not made up of primordial back holes

A research team led by Masahiro Takada at Kavli Institute for the Physics and Mathematics of the Universe used the Subaru Telescope to capture successive images of the Andromeda Galaxy. If there are many primordial black holes, a potential candidate for dark matter, their gravity should occasionally amplify light from stars in the Andromeda Galaxy. However, the researchers detected such an amplification only once during the observation period, confirming for the first time that dark matter is not made up of primordial back holes.

Integrating NAOJ's Technologies into Society

Aiming to achieve new breakthroughs in astronomy, NAOJ has developed and refined its own technologies to create its world-leading observing facilities. The "technologies for astronomy" that we

A CCD Camera for Spaceguard

Based on the technology used in HSC mounted on the Subaru Telescope, NAOJ developed a CCD camera for the 1-m telescope at the Bisei Spaceguard Center in cooperation with the Japan Aerospace Exploration Agency and the Japan Space Forum. This camera has been used to find and track asteroids and space debris for 10 years and, by ensuring the safe operation of satellites, contributed to making our society more secure.

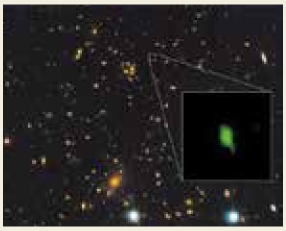
A CCD camera mounted on the telescope for tracking space debris.
Credit: JAXA

Megapixel CCD with High IR Sensitivity

In collaboration with Hamamatsu Photonics K.K., NAOJ developed a CCD with a 200-μm-thick depletion layer, dramatically improving the infrared sensitivity. As this sensor has a high X-ray sensitivity as well, it was also used in JAXA's Hitomi satellite. The same type of sensor is used in transmission electron microscopes (TEM). Its high sensitivity in X-ray is also valuable in medicine and can lighten the burden on patients by reducing the dose of X-rays required.

A newly developed megapixel CCD (2048 × 4096 pixels and 30 mm × 60 mm light receiving surface).

Selected Results from ALMA



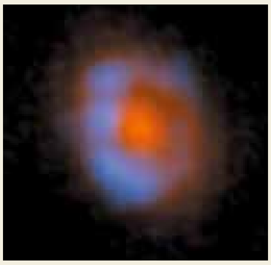
False color image of MACS1149-JD1, a galaxy located 13.28 billion light-years away. The oxygen distribution is shown in green.
Credit: ALMA (ESO/NAOJ/NRAO), NASA/ESA Hubble Space Telescope, W. Zheng (JHU), M. Postman (STScI), the CLASH Team, Hashimoto et al.

Oxygen in galaxies more than 13 billion light-years away

A research team led by Akio Inoue at Osaka Sangyo University used ALMA to detect oxygen in a distant galaxy 13.1 billion light-years away, and then in a more distant one 13.28 billion light-years away. With these discoveries, the record for the most distant galaxy with oxygen was broken twice. These results made great impacts on the worldwide galaxy formation research community.

Organic molecules around a young star

A research team led by Yuri Aikawa at the University of Tokyo and Jeong-Eun Lee at Kyung Hee University observed the young star V883 Ori using ALMA and detected various organic molecules including methanol, acetaldehyde, and acetone in the protoplanetary disk around the star. This result is remarkable, as it revealed the distribution of organic molecules in a planet-forming region.



The distribution of dust surrounding V883 Ori is shown in orange and that of methanol is shown in blue.
Credit: ALMA (ESO/NAOJ/NRAO), Lee et al.

The dust disk surrounding TW Hydrae.
Credit: ALMA (ESO/NAOJ/NRAO), Tsukagoshi et al.

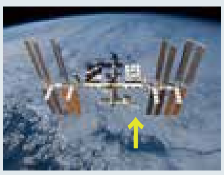
Formation site of ice giant planet

Takashi Tsukagoshi at Ibaraki University and his colleagues used ALMA to conduct detailed observations of a dust disk surrounding the young star TW Hydrae. The team found that the size of the dust particles in the inner one of the two gaps is smaller than that in the nearby regions. It is an important contribution toward understanding the formation of Neptune-size ice giants.

have developed in the process can be repurposed to benefit our lives and society. We intend to utilize the technologies for astronomy to make our society more secure, convenient, and healthy.

Earth-observing Instrument onboard the International Space Station

The Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) was an observational instrument installed on the International Space Station. Its mission was to detect the radio waves emitted by trace molecules in the Earth's atmosphere and reveal the fluctuations in their distributions.
NAOJ played a major role in the development of the sub-millimeter wave (640 GHz) receiver installed on the instrument.

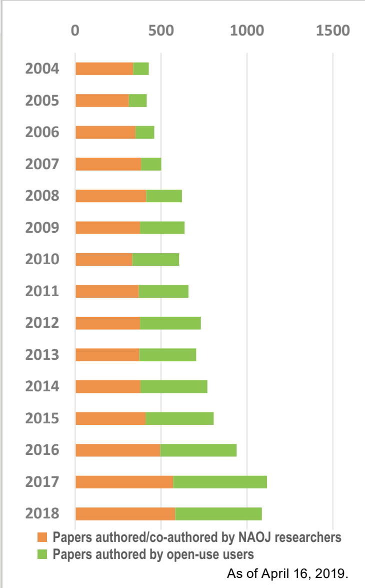


SMILES installed on the Japanese Kibo module. Credit: NASA

Published Papers Statistics

The number of papers published by NAOJ researchers has been increasing in tandem with the progression of the large projects. Through the open-use program, papers published by researchers affiliated with universities are also increasing.

Percentage of the top 10 % most cited papers written by NAOJ researchers: 16.2 % Percentage of the top 1 % most cited papers written by NAOJ researchers: 2.1 % Percentage of international coauthorship: 77.1 %
(2014 – 2018 Averages)



Operation of Okayama 188-cm Telescope and the Seimei telescope

The Subaru Telescope Okayama Branch Office has provided opportunities for observations using the Okayama 188-cm Reflector Telescope and the HIgh Dispersion Echelle Spectrograph (HIDES) for almost 20 years, and contributed to the development of research on exo-planets in Japan, including Japan's first detection of an exo-planet. At present, NAOJ is responsible for the open-use operation of the 3.8-m "Seimei" telescope of Kyoto University.

Collaboration with Universities

NAOJ operates observation facilities in collaboration with universities and institutions both in Japan and abroad.

The Optical and Infrared Astronomy Research and Education Network (OISTER) aims to conduct immediate follow-up observations of transient astronomical phenomena, such as supernovae, by organically connecting mid-to-small-size telescopes.

The Japanese VLBI Network combines radio telescopes operated by NAOJ and domestic universities to create a giant virtual radio telescope, through which we study the dynamics of gas in star-forming regions and gas jets blasting out from black holes.

Leading Astronomy Outreach Initiatives Globally

The International Astronomical Union (IAU) Office for Astronomy Outreach (OAO) is the IAU's international office for outreach located at NAOJ Mataka Campus, in Tokyo. The OAO is a joint venture between the IAU, the largest association of professional astronomers in the world, and NAOJ. It's responsible for leading the IAU's global communications and accessibility initiatives and for supporting the international network of National Outreach Coordinators (NOCs) located in more than 100 countries. This successful collaboration is one of the many initiatives for internationalization and diversity at NAOJ.

Graduate Course Education

NAOJ makes an effort to educate graduate students who will become leaders in the next generation. Through international education and research in cutting-edge research facilities, we aim to develop not only world-leading researchers and innovative engineers but also individuals who are able to contribute to wider society.

NAOJ accepts graduate students through the following three programs.

❶ The Graduate University for Advanced Studies (SOKENDAI)
SOKENDAI, School of Physical Sciences, Department of Astronomical Science is a graduate school based at NAOJ.

❷ Cooperative Graduate School Program

❸ Visiting Graduate Students Program

Number of Graduate Students (as of April 1, 2019)

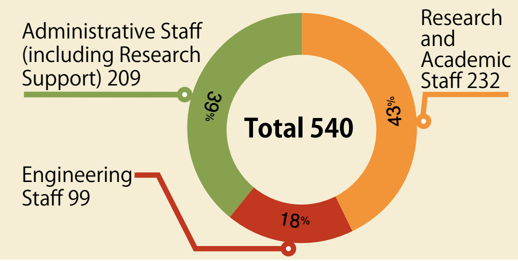
Students from SOKENDAI (five-year doctoral course) ……26
Students from cooperative graduate schools……26
Visiting graduate students……9

NAOJ accepted students from the following graduate schools in the last five years.

Tohoku University, Yamaguchi University, the University of Electro-Communications, the University of Tokyo, Japan Women's University, Kagoshima University, the University of Tsukuba, Tokyo University of Agriculture and Technology, Tufts University, Hosei University, the Open University of Japan, Osaka Prefecture University, Kyushu University, Shizuoka University, Hiroshima University, Nihon University, Meisei University, Tokai University, Tokyo Institute of Technology, Toho University, International Christian University (in random order)

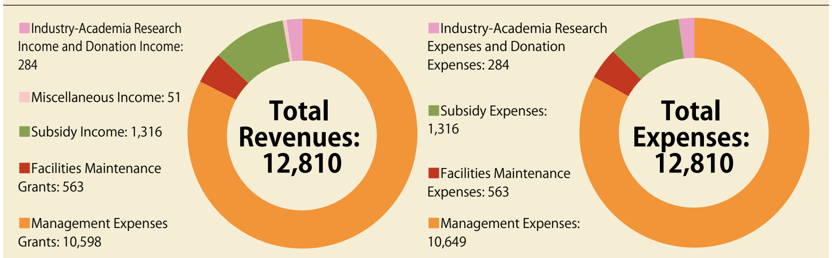
Profile of NAOJ

■**Number of Employee** (as of April 1, 2019)



■**Budget** (FY 2018)

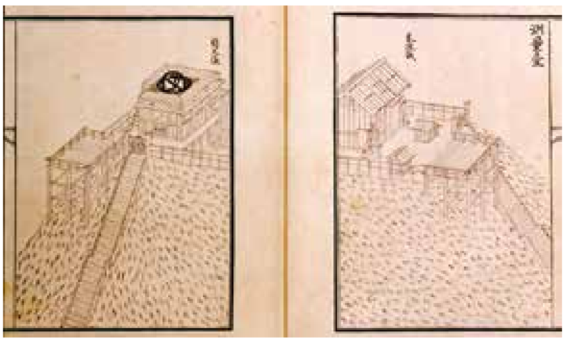
Unit: 1 million yen



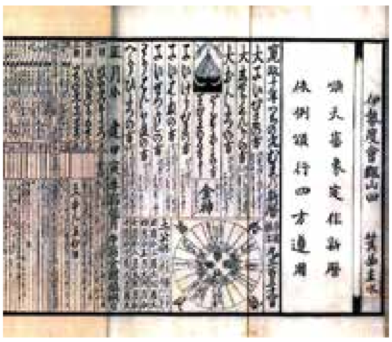
History of NAOJ

Tradition and Innovation: playing a part in Japan's natural science research

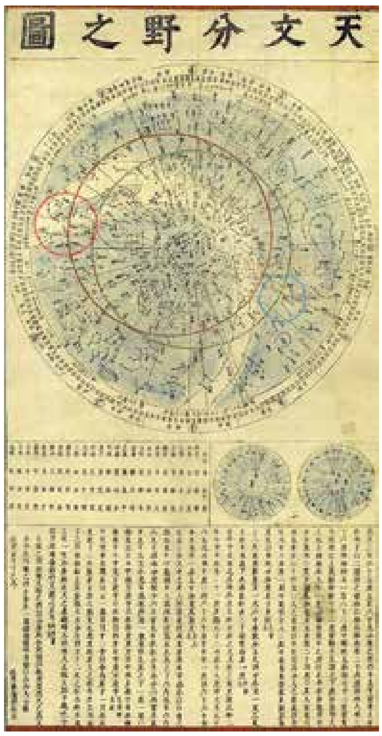
The origin of NAOJ dates back to the late Edo Era (more than 300 years ago) when the Shogunate Tenmonkata started observations of celestial objects to create ephemerides. NAOJ still carries on the compilation of ephemerides as a part of its duties. The Meiji Era saw the inflow of knowledge about modern astronomy from the West, and as a result, the Tokyo Astronomical Observatory and the Latitude Observatory were established in 1888 and 1899 respectively. Thereafter, Japanese astronomers developed various observing instruments and conducted much research over the next 100 years. Then, in 1988, the Tokyo Astronomical Observatory of the University of Tokyo, the Latitude Observatory, and a part of the Nagoya University Research Institute of Atmospherics were integrated to establish NAOJ. Let's briefly look back on the history of NAOJ which has always been a pioneer at the leading-edge of astronomy research.



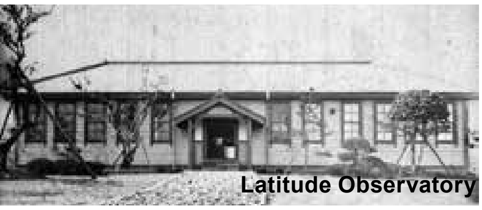
The Astronomical Observatory in Asakusa in the Edo Era (From Treatise on the Kansei Calendar).



Kansei Calendar enacted in 1798, Kansei Era 10.



Tenmon Bun'ya No Zu: Chart of the Constellations and the Regions they Govern published by Harumi Shibukawa (the first Shogunate Tenmonkata, also known as Yasui Santetsu) in 1677, Enpō Era 5.


Latitude Observatory

1888 The Tokyo Astronomical Observatory was established by the Faculty of Science, the University of Tokyo.

1899 The Latitude Observatory was established in Mizusawa.

1914 The Tokyo Astronomical Observatory was relocated to Mitaka Campus.

Rika Nenpyo

Since its first publication in 1925, we have been publishing Rika Nenpyo for over 90 years in cooperation with many research organizations.


Mitaka Campus in the early Showa Era.


65-cm Refractor Telescope


Nobeyama Millimeter Array


Laser Interferometer Gravitational Wave Antenna (TAMA300)


ALMA

1925 Publication of “Rika Nenpyo” began.

1926 65-cm Refractor Telescope Dome was constructed.

1929 65-cm Refractor Telescope was installed.

1930 Solar Tower Telescope (Einstein Tower) was completed.

1946 Publication of Almanacs and “Calendar and Ephemeris” began.

1949 The Nagoya University Research Institute of Atmospherics was established. Norikura Solar Observatory began observations.

1960 Okayama Astrophysical Observatory began observations.

1962 Dodaira Observatory began observations.

1969 Nobeyama Solar Observatory began observations.

1974 Kiso Observatory began observations.

1982 Nobeyama Radio Observatory began observations.

1988 The National Astronomical Observatory of Japan was established. Kiso Observatory was integrated into the University of Tokyo.

1992 Nobeyama Radioheliograph began observations.

1999 Subaru Telescope began observations. Laser Interferometer Gravitational Wave Antenna “TAMA300” began observations.

2000 Visitors’ Area opened at Mitaka Campus. Dodaira Observatory was closed.

2001 Agreement on ALMA project codified by Europe, the United States, and Japan. VERA Stations began observations.

2004 NAOJ was incorporated as the National Astronomical Observatory of Japan, National Institutes of Natural Sciences.

2006 Ishigakijima Astronomical Observatory began observations. HINODE began solar observations.

2007 As part of the Four-Dimensional Digital Universe (4D2U) project, the tridimensional dome theater was completed. The Lunar Explorer “KAGUYA” was launched and began observations.

2010 Norikura Solar Observatory was closed after 60 years of service.

2011 ALMA Early Science observation started.

2013 ALMA Inauguration Ceremony was held.

2014 TMT International Observatory was established. NAOJ participated as an initial member.

2015 Nobeyama Solar Observatory was closed.

2018 Okayama Astrophysical Observatory was closed. Supercomputer ATERUI II began operation.


Solar Tower Telescope


Nobeyama 45-m Radio Telescope


Subaru Telescope

NAOJ: Pioneering the Future of Astronomy

There are three main themes in 21st-century astronomy: the search for extraterrestrial life; understanding the beginning of the Universe; and understanding the nature of dark matter and dark energy. At present, major countries around the world are racing to construct large observing facilities to tackle these subjects. In this era of international cooperation and competition, the National Astronomical Observatory of Japan (NAOJ) actively conducts scientific research based on the following three mission statements: developing and constructing large-scale cutting-edge astronomical research facilities and promoting their open access aiming to expand our intellectual horizons; contributing to the development of astronomy as a world leading research institute by making the best use of a wide variety of large-scale facilities; and bringing benefits to society through astronomy public outreach.

Modern Japanese astronomy began when Harumi Shibukawa (Santetsu Yasui) completed an original calendar, the Yamato-reki (also called Jokyo-reki), in 1684. The earliest forerunner of NAOJ was the Astronomical Observatory in Asakusa of the Tenmonkata (Shogunate Astronomer) established in the late Edo Era. In 1888, the Astronomical Phenomenon Observatory of the University of Tokyo, Navy Meteorological Observatory, and the Geographical Bureau of the Home Ministry were integrated to form Tokyo Astronomical Observatory of the University of Tokyo in Azabu (which was then relocated to the present location in Mitaka in 1924). Then, in 1988, Tokyo Astronomical Observatory was combined with the Latitude Observatory and part of the Nagoya University Research Institute of Atmospherics to establish NAOJ in its modern form. In this way, NAOJ has experienced Japan's modernization throughout its long heritage, which can be seen if you walk around Mitaka Campus and view the number of beautifully preserved Registered Tangible Cultural Properties.

In 1999, after nine years of construction and more than a century after the dawn of modern Japanese astronomy, NAOJ completed the Subaru Telescope, an 8.2-m optical-infrared telescope embodying Japanese technology, near the 4200-m summit of Maunakea in Hawaiʻi. Although this year marks 20 years since its first light, the Subaru Telescope is still expected to achieve significant results throughout the 2020s with its ultra-wide-field-of-view unattainable on other large telescopes. Following the Subaru Telescope, NAOJ contributed to construction of the Atacama Large Millimeter/submillimeter Array (ALMA), composed of 66 antenna elements, on a 5000-m plateau in Chile in collaboration with North American, European, and East Asian partners. ALMA started its first observations in 2011 and has achieved significant accomplishments. NAOJ is now constructing the Thirty Meter Telescope (TMT), an optical-infrared telescope with a 30 meter aperture, on Maunakea in collaboration with the United States, Canada, China, and India.

Besides these, NAOJ is a partner in KAGRA, the Large-scale Cryogenic Gravitational Wave Telescope led by the University of Tokyo. Once it is completed, NAOJ will be an international hub for multi-messenger astronomy. In addition, ATERUI II, the world's fastest supercomputer for astrophysical calculations, is generating synergies between observations and theoretical/numerical simulations with its peak performance of 3 Petaflops. Other projects have also achieved glorious results, including not only the Hinode Solar Observatory, which was developed in collaboration with JAXA, NASA, and other agencies, but also the lunar orbiter SELENE (Kaguya), the space VLBI satellite HALCA, and two CLASP sounding rocket experiments. NAOJ will continue our efforts on space missions by leveraging our scientific and technological assets.

Image from a simulation of dark matter halo structure and evolution.
(Simulation: Tomoaki Ishiyama, Visualization: Hirotaka Nakayama, NAOJ 4D2U Project.)

During the development from the Subaru Telescope to ALMA, significant scientific discoveries have seamlessly continued to be made, such as the discovery of the most distant galaxies in the Universe; amazing images of protoplanetary disks in which exoplanets are forming; and the world's first extensive 3D map of dark matter. In the near future we expect that the true nature of dark matter and dark energy will come to light, a detailed model of planet formation will be established, and valuable insights into exo-planet environments that could harbor life will be obtained. These achievements will enhance Japan’s international presence, stimulate an interest in science among the Japanese people, especially the younger generation, and instill pride and confidence in them.

As an open-use institute for universities, NAOJ mediates different opinions within research communities as well as developing large observational facilities that cannot be supported by individual universities and promotes their open use. Nowadays, astronomy is rapidly becoming interdisciplinary and its domain is expanding into basic physics, chemistry, and life science, and NAOJ serves as a hub for such expanding research. Perusing an advanced science like astronomy needs a significant budget for construction and operation. On the other hand, in view of Japan’s severe financial situation, we must continuously review the merits of existing research facilities and leverage the technological assets of NAOJ to address issues that industry faces and contribute to national endeavors.

In the not-so-distant future, I believe, environments harboring life will be discovered on planets beyond the Solar System. Then, finding alien civilizations will become the next frontier for astronomy. With your continued support we can expect the field of astronomy, which has been nurtured for more than three centuries in Japan, and NAOJ in particular, to be vigorous in the future.

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