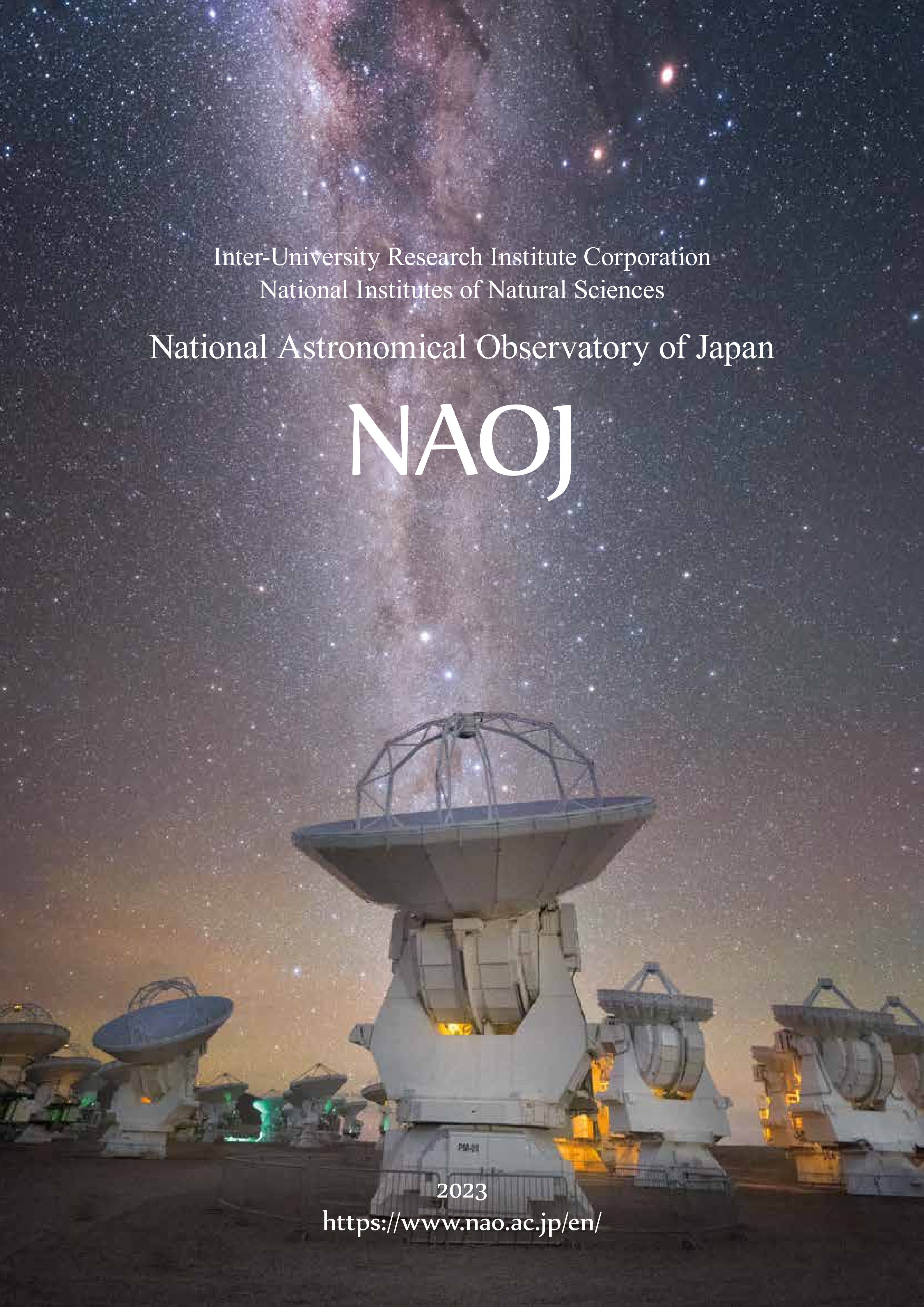
Inter-University Research Institute Corporation
National Institutes of Natural Sciences

National Astronomical Observatory of Japan

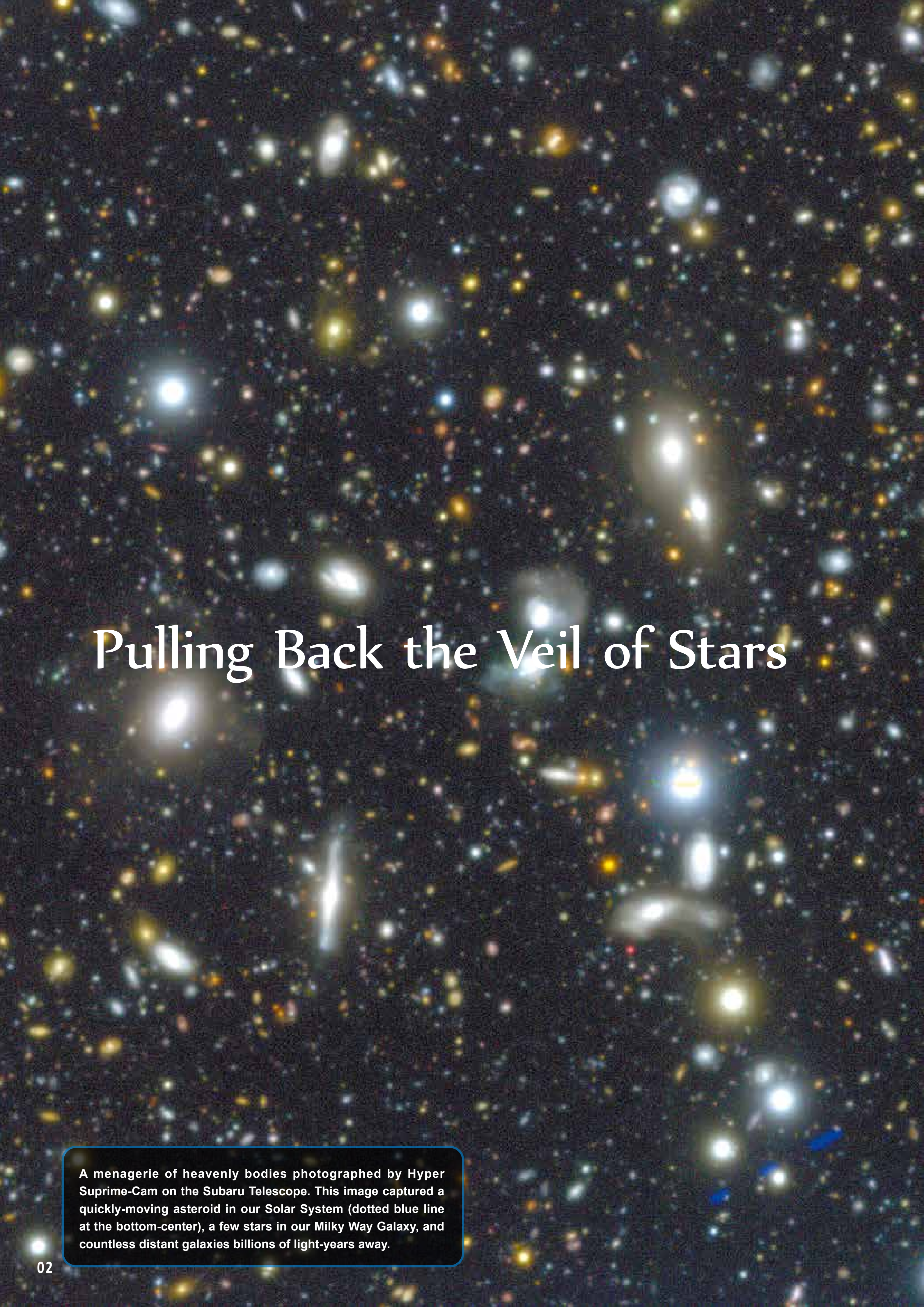
NAOJ



2023

https://www.nao.ac.jp/en/

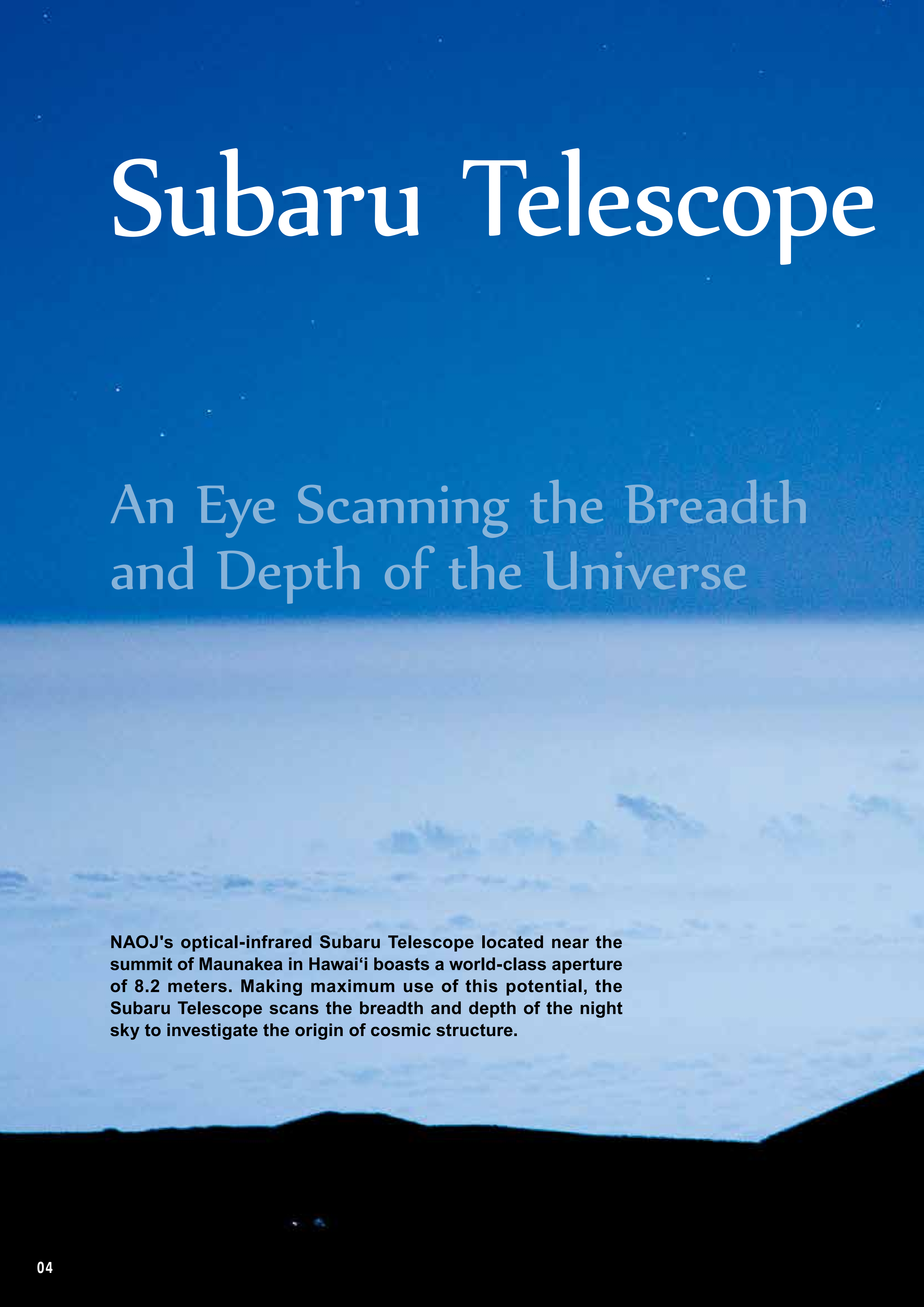
Pulling Back the Veil of Stars



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: ALMA Antennas and the Southern Milky Way
Back Cover Photo: Subaru Telescope and the stars of the northern sky
Production Staff: Masaaki Hiramatsu (Editor in Chief), Hiroyuki Takata, Maki Kubo, Ramsey Lundock (NAOJ Publications Office)
Published by the National Astronomical Observatory of Japan



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 Hawaiʻi: 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.

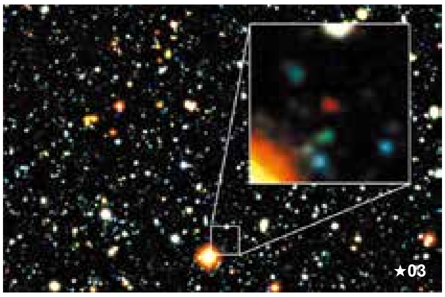
Subaru Telescope

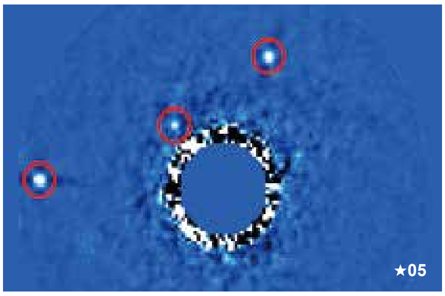
Investigating the Mysteries of Omnipresent Dark Matter and Dark Energy

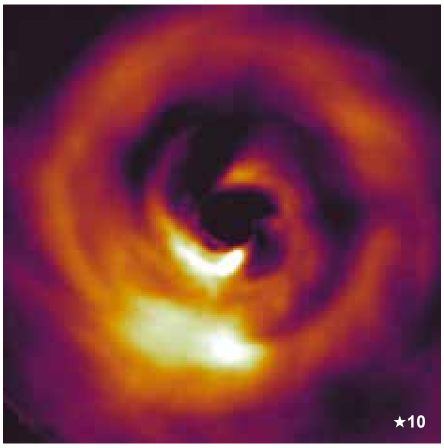
The Universe is filled with a mysterious substance known as "dark matter"; and a mysterious energy known as "dark energy" is accelerating the expansion of the Universe. It is necessary to unveil the nature of dark matter and dark energy in order to understand the evolution and the physics of the Universe. 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 currently under development capable of observing approximately 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







★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 area 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 Jupiter's stratosphere imaged in mid-infrared (NAOJ/ NASA JPL-Caltech)
★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"

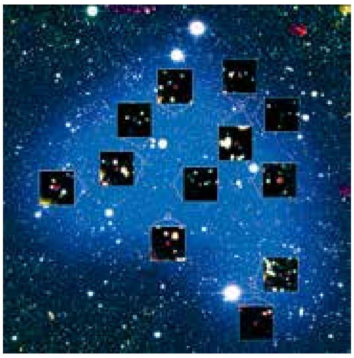
The Subaru Telescope is located in the summit region of Maunakea at an altitude of 4139 meters. It is one of the best sites in the world for astronomy with many clear nights and stable air flow. Maunakea hosts 13 telescopes from 11 countries, one of the largest collections of leading-edge astronomy observation 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 2021, it has contributed to an outstanding total of 2476 papers and 164 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. The Strategic Program using Hyper Suprime-Cam (HSC) to photograph 400,000 galaxies has been completed and now researchers are processing and analyzing the huge amount of data. 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) 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.



The farthest observed galaxy protocluster, z66OD, located 12.97 billion light years away, as observed by HSC on the Subaru Telescope. The member galaxes of the protocluster are indicated by boxes. The Subaru Telescope's ultra-wide field of view is useful for searching for unknown distant objects, which could be lurking anywhere. HSC's unrivaled capabilities make the Subaru Telescope an important instrument in world astronomy for exploring deep space.

Upgrading to Super Subaru Telescope with “Subaru Telescope 2.0.”

Launched in 2022, Subaru Telescope 2.0 will break new ground in astronomy with next generation facility instruments.

The wide-field multi-object spectrograph, Prime Focus Spectrograph (PFS), is mounted at the prime focus of the Subaru Telescope. It can simultaneously observe up to 2,394 objects across its 1.3 degree diameter field-of-view. (top) One of the spectrograph modules in the telescope dome. (bottom) The Prime Focus Instrument, together with the Wide Field Corrector, mounted at the prime focus of the telescope.

Subaru Telescope

Subaru Telescope Science 03

Discovery of Earth-like Exo-Planets

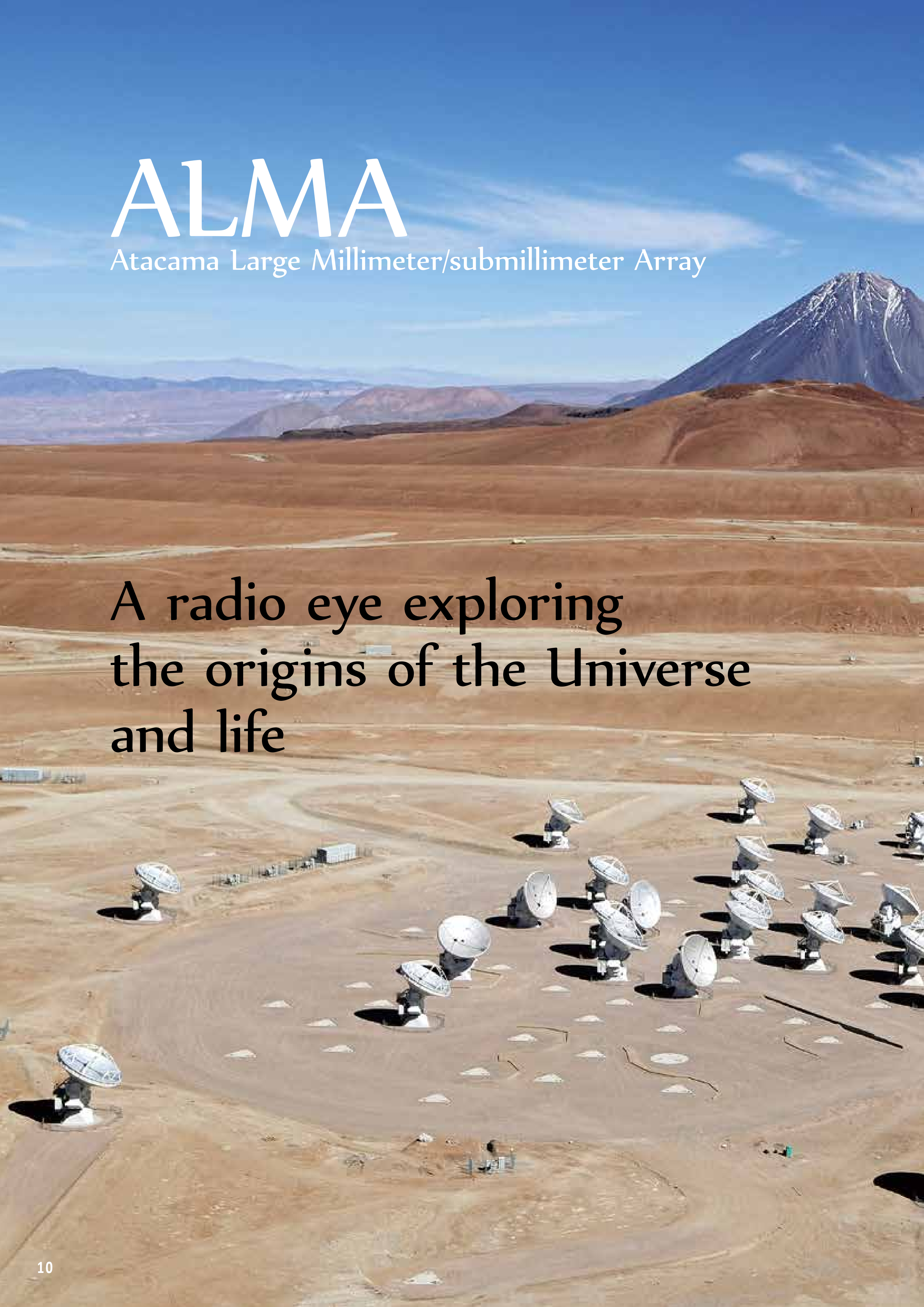
Over 5000 exo-planets have been discovered to date. The Subaru Telescope is also displaying its strength through observations of those exo-planets. In 2013, making the best use of the Subaru Telescope’s high sensitivity, it directly imaged the dimmest planet at that time. Among exo-planets, Earth-like 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 Doppler instrument to accurately measure line-of-sight velocities 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. 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

A radio eye exploring the origins of the Universe and life



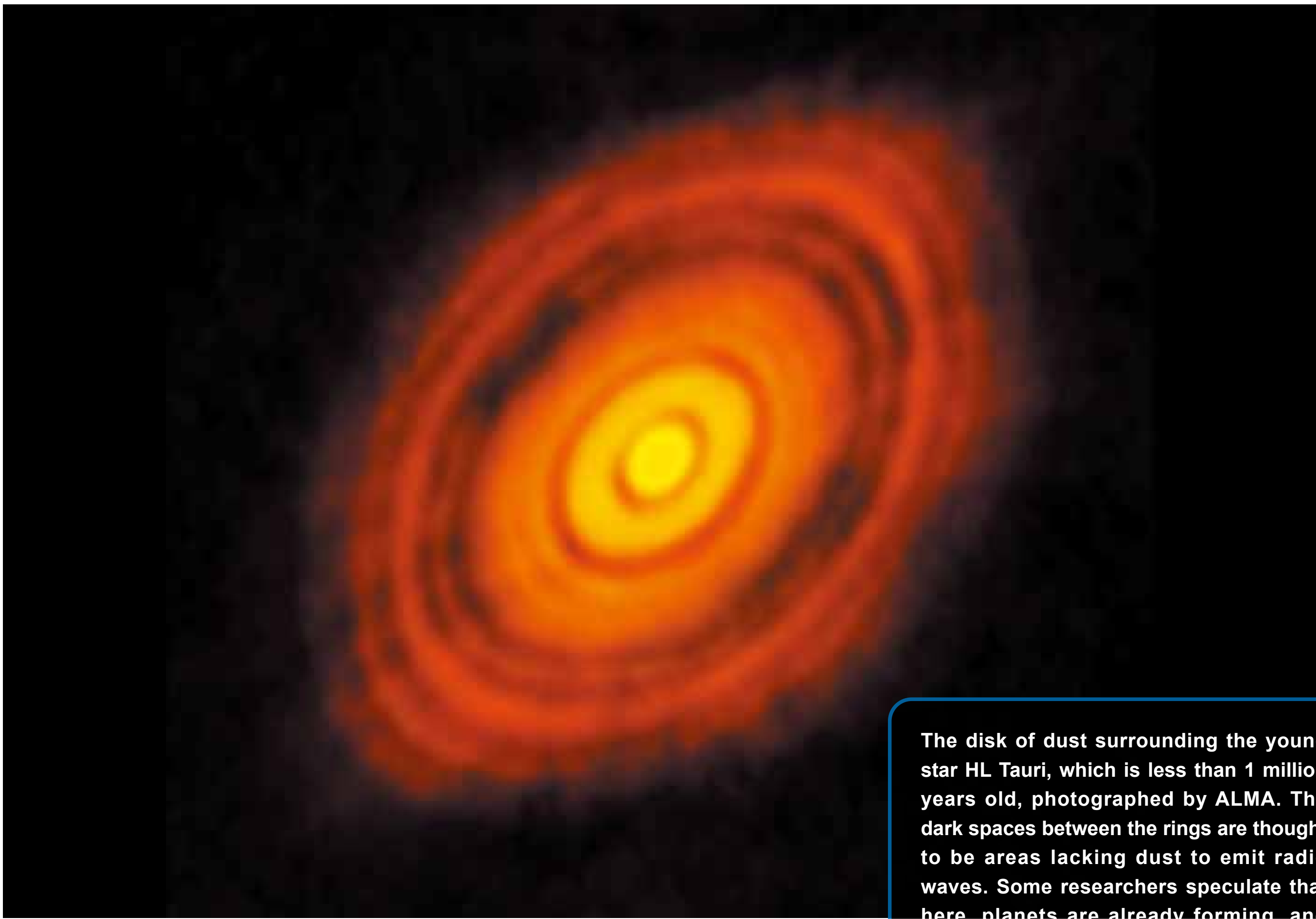
Located in the Atacama Desert, ALMA is one of the world's highest capability radio telescope arrays, achieved through an international collaboration including NAOJ, North America, Europe, and other partners. The 66 individual antennas function together as a single giant radio telescope. Its radio observations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

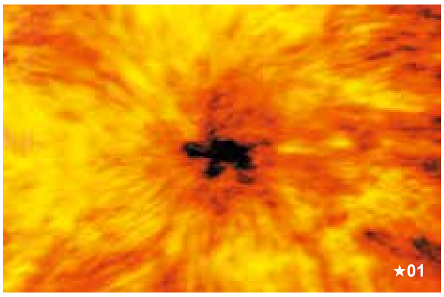
Unlocking the Mysteries of Star and Planet Formation

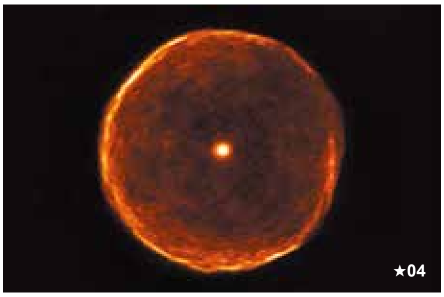
Newborn stars and planets still in the process of forming lurk in the night sky. The diffuse clouds of interstellar gas and dust are the material for stars and planets. These clouds gradually compact, and in their centers stars and planets are born. These newborn stars are hidden inside the parent clouds, 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.

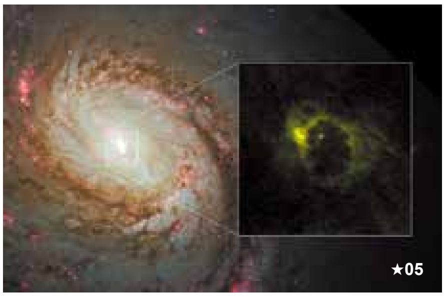
Disks comprised of gas and dust revolve around young stars, with ages between 100 thousand and 10 million years. These protoplanetary disks are the sites of planet formation. ALMA's high angular resolution has revealed concentric ring structures in the disks, as well as disks with spiral or crescent 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.

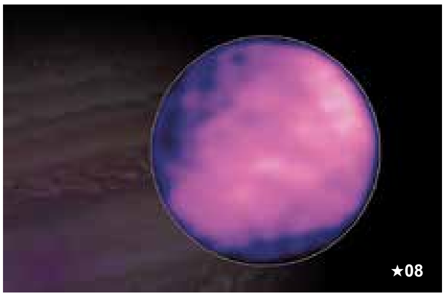
The spiral shaped protoplanetary disk around the young star Elias 2-27 photographed by ALMA. Credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

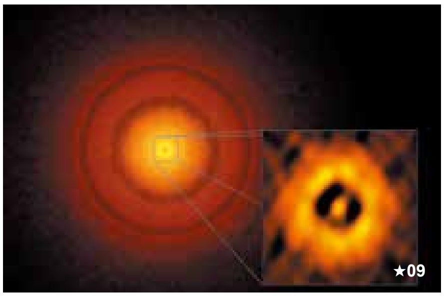
ALMA Gallery

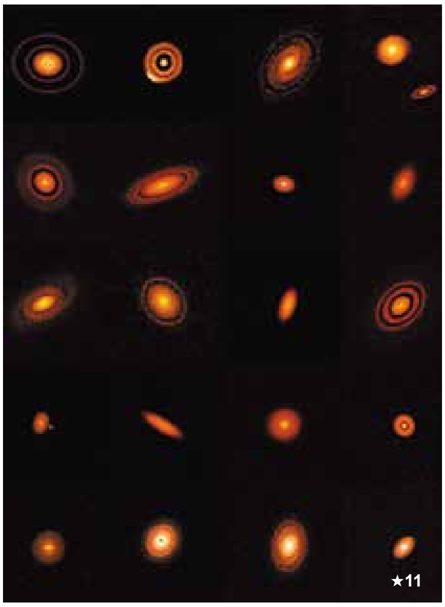


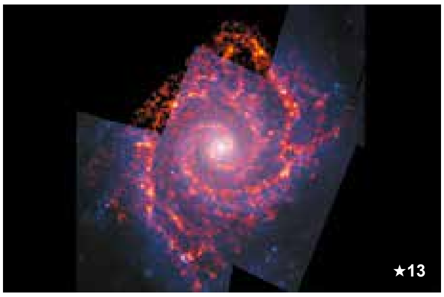












★01 A sunspot photographed by ALMA
★02 ALMA Trilateral Agreement Signing Ceremony
★03 ALMA Morita Array
★04 ALMA image of the gas around the star U Antliae
★05 Close-up of the center of spiral galaxy M77
★06 ALMA Control Room
★07 A 7-meter antenna being transported to the Array Operations Site
★08 The 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 Spiral Galaxy M74

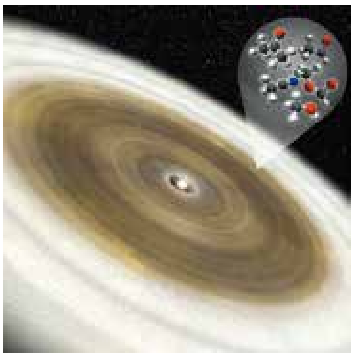
Credit: ★04 ALMA (ESO/NAOJ/NRAO)/F.Kerschbaum ★05 ALMA (ESO/NAOJ/NRAO), Imanishi et al., NASA/ESA Hubble Space Telescope and A.van der Hoeven ★08 ALMA (ESO/NAOJ/NRAO), S. Trumbo et al.; NRAO/AUI NSF, S. Dagnello; NASA/ESA Hubble Space Telescope ★09 S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO) ★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 NRAO/AUI/NSF, B. Saxton: ALMA (ESO/NAOJ/NRAO); NASA/Hubble ★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!

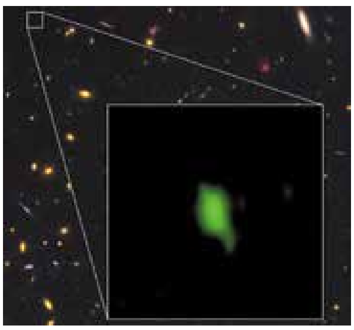
ALMA receivers developed at NAOJ. From left to right: Band 4 (millimeter wave, 125~163 GHz), Band 8 (submillimeter wave, 385~500 GHz), Band 10 (terahertz, 787~950 GHz).
Credit: ALMA (ESO/NAOJ/NRAO)

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. At the time, this was the record for the most distant (and therefore earliest) galaxy where oxygen had 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 how much 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.

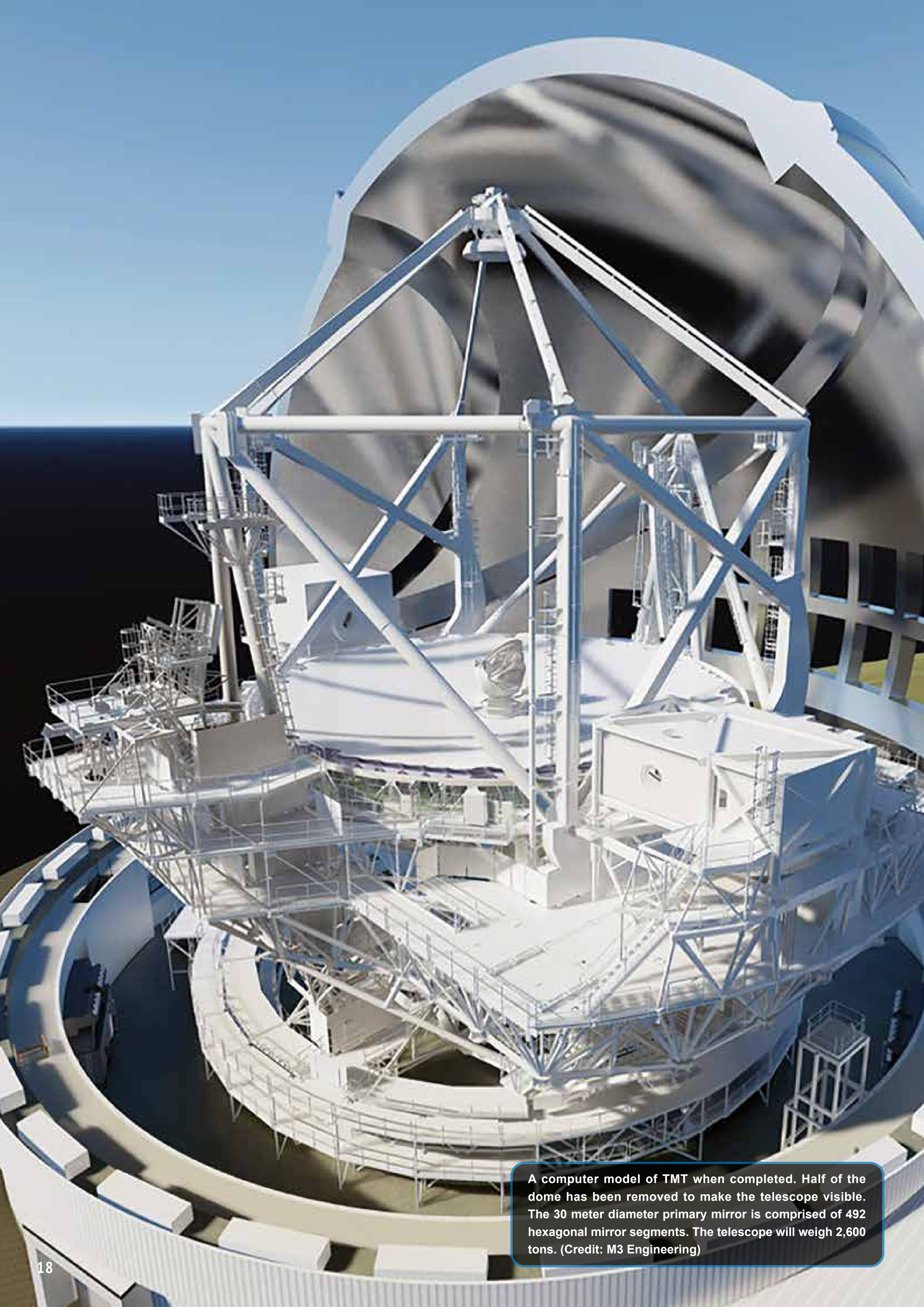


Thirty Meter Telescope TMT

An Eye Searching Planets for Extraterrestrial Life

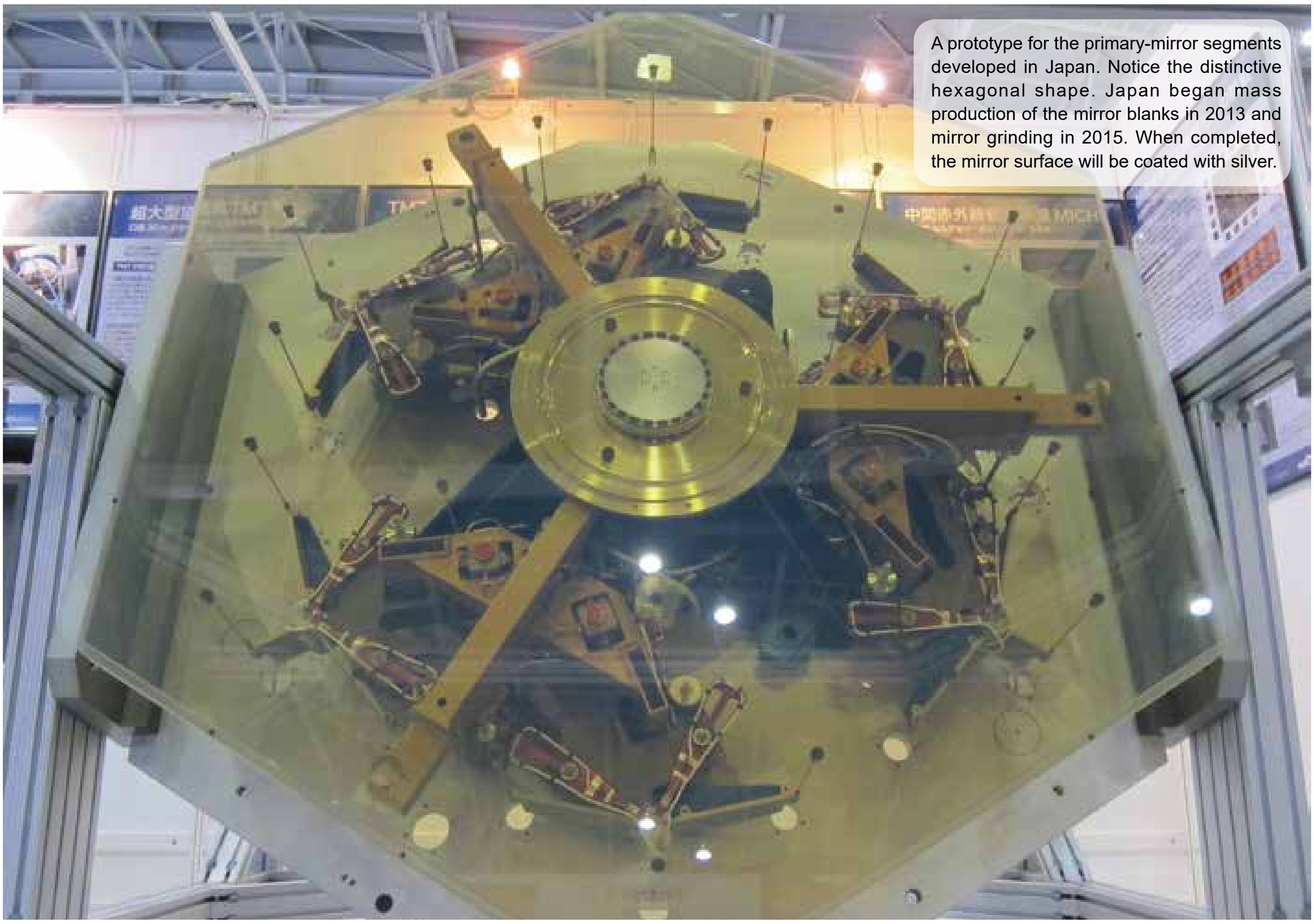
The Thirty Meter Telescope (TMT) is an optical-infrared telescope under construction in the summit region of Maunakea by a collaboration of five countries, Japan (represented by NAOJ), the United States, Canada, China, and India. With its 30 meter primary mirror, it will achieve high sensitivity and 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 about 5 times better than the James Webb 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. The telescope will weigh 2,600 tons. (Credit: M3 Engineering)

TMT Science 01

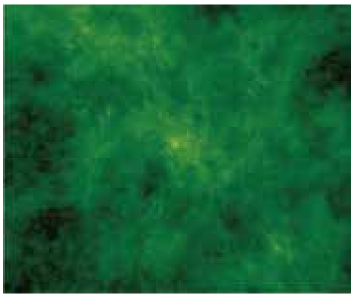


A prototype for the primary-mirror segments developed in Japan. Notice the distinctive hexagonal shape. Japan began mass production of the mirror blanks in 2013 and mirror grinding in 2015. When completed, the mirror surface will be coated with silver.

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 orbits at special angles to the Earth, TMT will also be capable of spectroscopic analysis of the atmosphere of the planet. TMT has the ability to detect the characteristic colors of plants, as well as oxygen and ozone produced by plants, and organic molecules of biological origin. TMT will explore the universality of life in the Universe as yet unknown to humankind.



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 March 2022, 356 mirror blanks have been produced.
Credit: NAOJ/OHARA

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

A simulation of what the center of M31 will look like when observed by TMT (top) compared with an actual observation by the Hubble Space Telescope (bottom). TMT will deliver over 10 times better resolution than the Hubble Space Telescope.
Credit: T. Do/Dunlap Institutes/IRIS

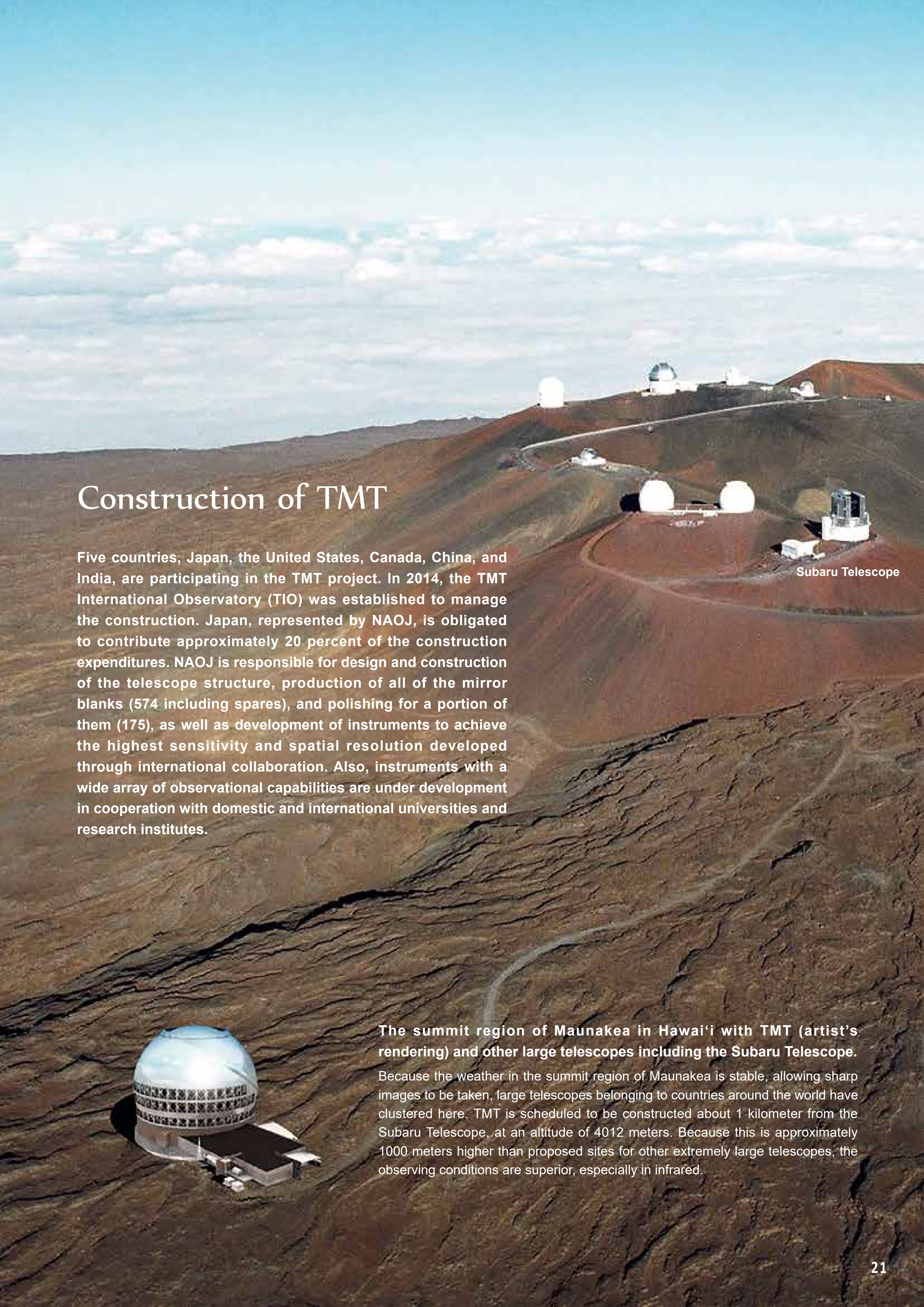
TMT Science 03

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 energy.

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.



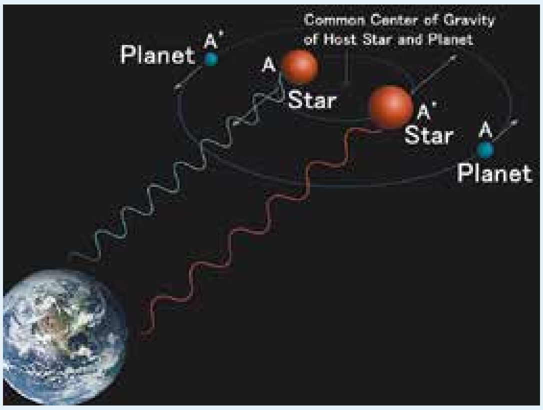
The summit region of Maunakea in Hawai‘i with TMT (artist’s rendering) and other large telescopes including the Subaru Telescope.

Because the weather in the summit region of Maunakea is stable, allowing sharp images to be taken, 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

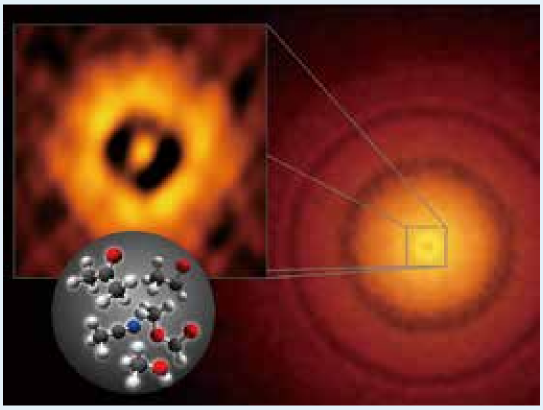
Detailed observations of the increasing number of exo-planets and protoplanetary disks, and searching for life in the Universe are the largest goals for 21st century astronomy. Together the Subaru Telescope, ALMA, and TMT form a winning team in the "search for life."



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.

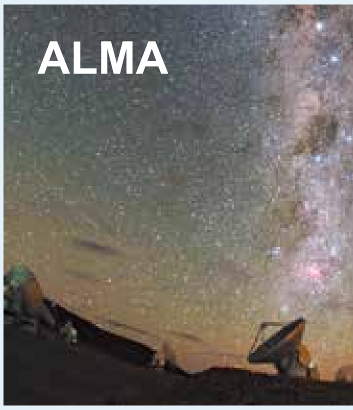
The host star moves in reaction to the planet's orbital motion. Planets can be detected indirectly via spectroscopic observations of the Doppler effect produced in the light from the host star.

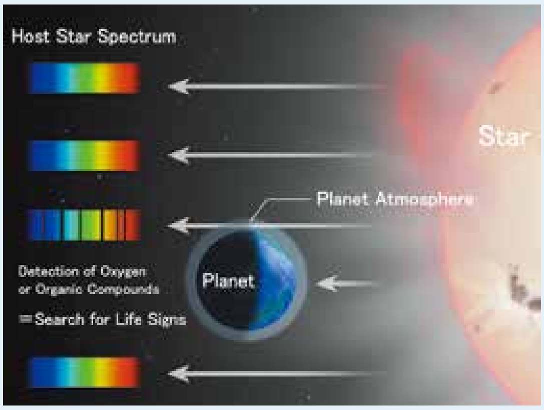


Finding Building Blocks for Life

ALMA devotes its energies to observations of formation sites of planets as 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 the origin of 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.

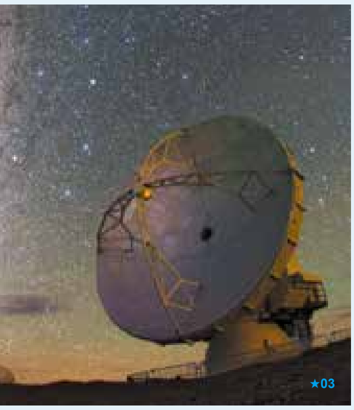
② The Search for the First Stars

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.

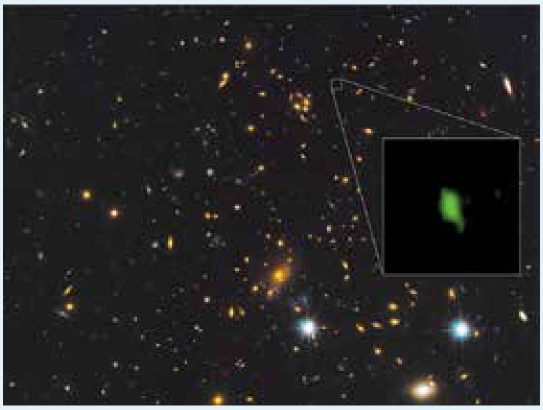


★03

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.

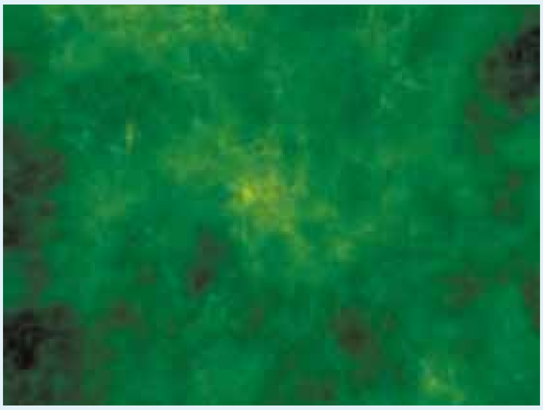
ALMA false color image (green zoom-in inset) showing the oxygen in the galaxy MACS 1149-JD1 located 13.28 billion light-years from Earth.★02



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

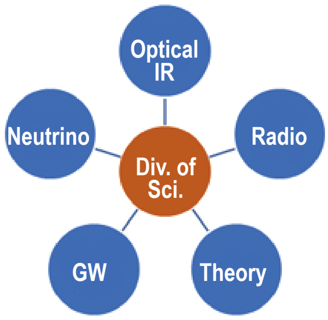
Despite the fact that dark matter and dark energy play critical roles in the formation of celestial objects and the accelerating expansion of the Universe, their true natures remain a mystery. The Subaru Telescope elucidates the 3D distribution of dark matter over wide areas through observations of gravitational 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.

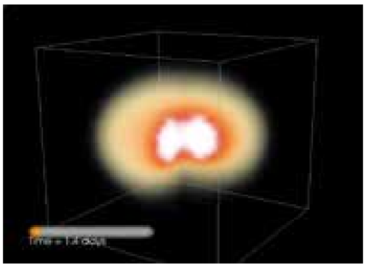
Under the keywords "fusion of theory and observation", "multi-wavelength astronomy", and "multi-messenger astronomy", members of the Division of Science conduct research to advance modern astronomy based on their own original ideas, unimpeded by the traditional divisions between observation wavelengths 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.



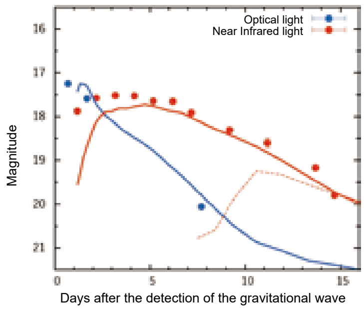
A diagram of the Division of Science's goal of unified astronomy utilizing various techniques.

Examples Combining Theoretical and Observational Research

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

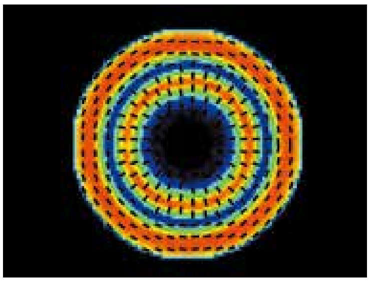


Credit: Masaomi Tanaka

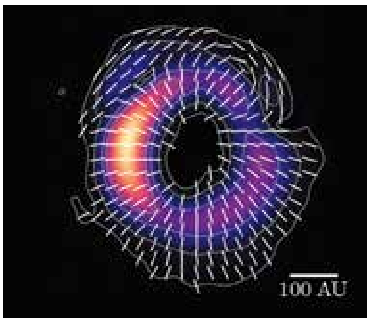


The origin of gold and rare-earth metals in the Universe had been a longstanding mystery, but we now know that they are produced in "neutron star mergers." A neutron star is the object that remains after a massive star finishes its life in a supernova. Theoretical research and simulation studies using 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.

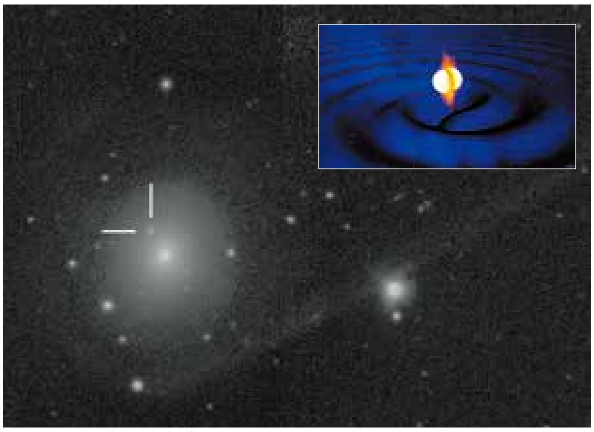
The theoretical prediction of the polarization of radio emission from a protoplanetary disk (upper image, black bars indicate the direction of the polarization, image color indicates the degree of polarized emission) and the polarized radio emissions from the protoplanetary disk around the young star 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 for the first time, throwing open the gates of multi-messenger astronomy. With the addition of the Large-scale Cryogenic Gravitational Wave Telescope KAGRA, 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?

The Infrared Doppler Instrument (IRD, right photo), a near infrared very high precision spectrometer for the study of exo-planets, developed through collaboration between the Astrobiology Center, NAOJ, and universities was mounted on the Subaru Telescope in 2018. A large-scale observing program is underway. This project discovered its first exo-planet in 2022. This planet orbits a star cooler than the Sun, and could conceivably have liquid water on its surface.

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 2600 ton telescope structure with a high precision better than one-thousandth 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.

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: 21 domestic, 11 overseas

As of September 28, 2022.

Notable Patents

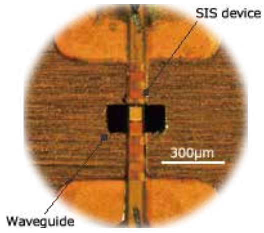
Adaptive Optics Systems and Optics Equipment, Patent No. 6394850 (patented in Japan and the United States)

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.

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.

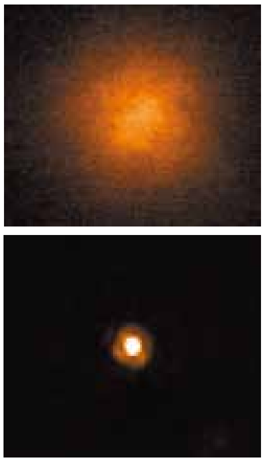
NAOJ has specialized cleanroom equipment for developing superconducting devices and has realized steady production of superconducting components with world-leading performance. Here, we produced ALMA receivers including its highest frequency band (950 GHz). There are only a few facilities in the world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



Superconducting device for ALMA’s highest frequency receiver.

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. The same technology can be used for observing the Earth from space, transmitting light signals to space, ophthalmology, or observing living cells under 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 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.

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 "Study 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", "RISE Project", "SOLAR-C Project" (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, is constructing large-scale, low-frequency interferometers in Australia and South Africa.

Subaru Prime Focus Spectrograph Project

The PFS fiber module. Actuators align each optical fiber to a different celestial object so that the light from many targets 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 (Prime Focus Spectrograph) will allow simultaneous spectral observations of up to approximately 2400 celestial objects across a wide field of view of 1.3-degree diameter. Capable of spectra across a broad wavelength band from optical through near infrared, it can efficiently measure the distances to distant galaxies and investigate the state of galaxies at different eras. PFS is being developed through international collaboration among 12 institutions from 7 countries and regions led by the Kavli Institute for the Physics and Mathematics of the Universe, the University of Tokyo. 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 Science Project

The KAGRA vacuum duct.

Observations of the Universe through gravitational waves started in 2015 with the first direct detection of gravitational waves from the merger of two black holes. Now many gravitational wave events have been observed, and multi-messenger astronomy in combination with conventional telescopes is actively pursued. Together with ICRR, KEK, and other institutes, we are participating in the development and operation of the gravitational wave telescope KAGRA. KAGRA will make important contributions to the International Gravitational-Wave Observatory Network. New technologies are also being developed at the TAMA300 interferometer in NAOJ Mitaka Campus, producing world-leading results in quantum optics.

Center for Computational Astrophysics (CfCA)

ATERUI II

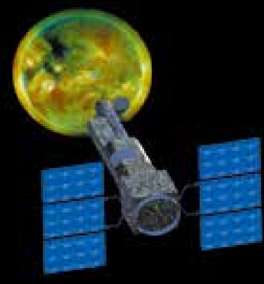
We promote the use of computer systems for simulation including ATERUI II; the world's fastest supercomputer for astrophysics (theoretical peak performance of 3 Pflops), research and development for simulation technology; and astronomy research using simulations. Our objective is to reveal aspects of 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 Solar Observing satellite “HINODE” (right)

Using the solar observing satellite “HINODE,” the Solar Flare Telescope in Mitaka, and the Nobeyama Radio Polarimeters, we obtain, compile, and publish the multi-wavelength data of solar magnetic activity. By observing the 3D structure and time evolution of the magnetic field from the solar surface to the upper solar atmosphere, research is progressing on dynamic activity such as jets and waves that heat the solar atmosphere as well as both the effects of sudden explosions in the inner heliosphere and their origins. Also, cutting-edge research and rocket and balloon experiments are conducted for the development of next generation ground and space-based solar observing instruments.

SOLAR-C Project



Solar-C Credit: NAOJ/JAXA

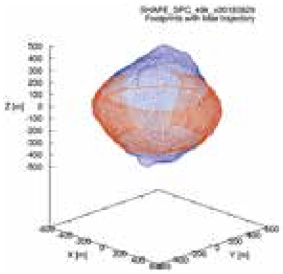
The hot chromosphere and corona above the solar surface are awash with fine jets and waves driven by the magnetic field. The next-generation satellite SOLAR-C can simultaneously observe all temperature ranges, from 20,000 degrees at the chromosphere to the over 2 million degree temperatures that appear in the corona during a flare, and will carry our understanding of solar magnetic energy release regions into a domain beyond the reach of the current solar observing satellite “HINODE.” SOLAR-C development, led by Japan with contributions from Europe and America, continues, aiming for a launch in the late 2020’s.

JASMINE Project

JASMINE

The JASMINE Project works to realize the satellite “JASMINE” to reveal the Milky Way’s central core structure and formation history by measuring the distances and the motions of stars through high-precision positional astronomy in the infrared and to explore the evolution history of the Milky Way. The satellite also aims to search for Earth-like habitable exoplanets by detecting the dimming when a planet transits in front of a red dwarf star smaller than the Sun. JASMINE has been selected as the JAXA-ISAS Competitive Middle-Class Science Missions No.3.

RISE Project



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

Investigating the interior structure of Solar System bodies reveals their origins and evolution. In JAXA’s lunar explorer “KAGUYA,” the RISE Project measured the Moon’s shape, investigated the gravitational field on the far side of the Moon precisely, and revealed the topography of the lunar surface, including the polar regions. Recently, it has developed a laser altimeter for the Asteroid Explorer Hayabusa2 with collaborators, and oversaw it’s operation and science observations. For future missions, RISE is leading international collaboration to develop the Ganymede laser altimeter for the European Jovian moons explorer and heading a sub science team for the Japanese Martian moons explorer.

★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.

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.

Nobeyama Radio Observatory

The Nobeyama 45-m Radio Telescope.

The 45-m telescope at Nobeyama Radio Observatory pioneered millimeter-wave astronomy in Japan. Utilizing its high sensitivity, we observe radio waves emitted from various interstellar molecules. We have especially focused on detailed observations of molecular gas clouds in star-forming regions and investigations of unusual molecular clouds near the center of the Milky Way. One of the fruits of our research is a completed catalog showing the evolution of the Orion molecular cloud complex.

Advanced Technology Center

Subaru Telescope's HSC being test-assembled in the laboratory.

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 instruments for TMT and new receivers for ALMA.

ASTE Project

10-m submillimeter antenna

The ASTE telescope (Atacama Submillimeter Telescope Experiment) is a 10-m diameter submillimeter telescope established in the Atacama Desert (altitude 4860 m) in Chile in 2002. Taking advantage of the wide-area, broad-waveband capabilities provided by a large-aperture, single-dish submillimeter telescope, it provides a platform for advanced research and development and pilot observations leading to future observations with ALMA. It conducts wide-field, submillimeter observations of molecular clouds in the Milky Way and nearby galaxies using the 490 and 810 GHz band receivers, and observational research on distant galaxies using the world's first on-chip superconducting spectrometer.

Public Relations Center

Regular Stargazing Party using the 50-cm Telescope.

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.

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 Finance)
  - 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 Science Project — Kamioka Branch Office
- TMT (Thirty Meter Telescope) 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
- ASTE 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

- Library
- IT Security Office
- Research Enhancement Strategy Office
  - Research Evaluation Support Office
  - Industry Liaison Office
- Office of International Relations
- Human Resources Planning Office
- Safety and Health Management Office
- Engineering Promotion Office
- Graduate Education 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 Project is constructing the 30 meter telescope TMT. The Gravitational Wave Science Project 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”, “RISE Project”, and “Solar-C Project.”

“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 throughout Japan and around the world in the best observational environments to explore the Universe.

NAOJ Mizusawa

Mizusawa VLBI Observatory (VERA)

NAOJ Mizusawa has a long history since its found ing as a part of the International Latitude Obser vatories. It operates VERA to observe the Milky Way, black holes, etc.

Center for Computational Astrophysics

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

RISE Project

The RISE Project has contributed to instrument development, observation operations, and space craft orbit estimation for KAGUYA and Hayabusa2, and has been carrying out research and develop ment for exploration of the satellites of Mars and Jupiter.

Japanese Branches

NAOJ Nobeyama

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 radio telescopes in the world. It has achieved epoch making results, such as discov ery of new interstellar molecules and detection of the signature of a supermassive black hole in a galaxy. Nobeyama Campus is open daily to the public.

GWSP Kamioka Branch, KAGRA

KAGRA, a gravitational wave telescope constructed in the Kamioka Mine, aims to expand the field of gravitational wave astronomy. The Kamioka Branch of the Gravitational Wave Science Proj ect supports the installation and commissioning of KAGRA.

Subaru Telescope Okayama Branch

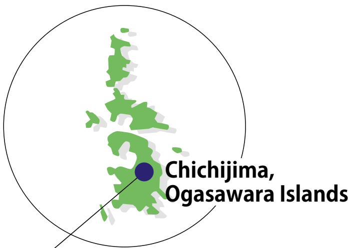
Open use observations are conducted by NAOJ at the 3.8 m telescope of the Okayama Observatory, the Astronomical Observatory of the Graduate School of Science, Kyoto University. Open use observing oppor tunities with the largest optical and near infrared astronomy facility in Japan are provided.

Mizusawa VLBI Observatory : Yamaguchi Station

Mizusawa VLBI Observatory : Ibaraki Station

NAOJ Mitaka

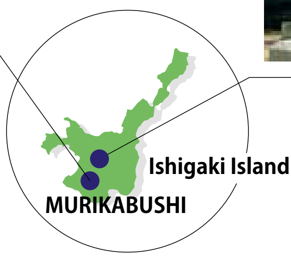
As the headquarters of NAOJ, Mitaka Campus houses offices of various projects and divisions, as well as administrative offices.



Mizusawa VLBI Observatory : Ishigaki-jima Station (VERA)

Ishigakijima Astronomical Observatory

MURIKABUSHI is a 105 cm telescope in Ishigakijima Astronomical Observatory.



Mizusawa VLBI Observatory : Iriki Station (VERA)

Mizusawa VLBI Observatory : Ogasawara Station (VERA)

Overseas Branches

NAOJ Hawai'i

Subaru Telescope, NAOJ TMT Project

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.

Hilo Base Facility

The base facility of Subaru Telescope is located in Hilo on the Island of Hawai'i. 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.

The Subaru Telescope (left)

An optical infrared telescope with a world class 8.2 meter aperture. Full scale observations started from FY 2000. In FY 2022, a new project called "Subaru Telescope 2.0" started to investigate the evolution of the Universe and the origin of elements with new core instruments.

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.

NAOJ Chile

NAOJ Chile, NAOJ ALMA Project

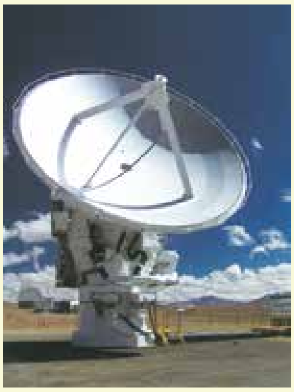
The Atacama Desert in northern Chile, one of the driest places on Earth, is an ideal location for short wavelength radio wave (millimeter and submillimeter wave) observation. ALMA and ASTE have been established here. The NAOJ Chile office and the Joint ALMA Observatory Santiago Central Offices are located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

ALMA

ALMA, led by NAOJ, the National Radio Astronomy Observatory (US), and the European Southern Observatory, is a giant radio telescope array with 66 antennas operated on a 5000 meter elevation plateau in Chile. NAOJ collaborates in East Asia with the Academia Sinica Institute of Astronomy and Astrophysics in Taiwan and the Korea Astronomy and Space Science Institute. Credit: ESO

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.
Credit: ESO

Public Access to NAOJ facilities

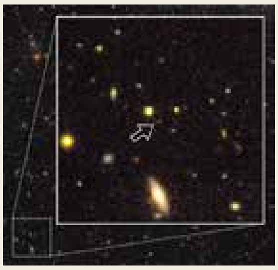
To widely disseminate our research results to the public, the major facilities of NAOJ offer visitors' areas, annual open house days, or regular stargazing parties.

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. We also give back to the community through activities to support university researchers and raise Japan's international profile including the compilation and publication of various astronomy data and open-use analysis environments by the Astronomy Data Center; collaborative research and facility use in the Advanced Technology Center; and the dissemination of research results in Japan and overseas by the Public Relations Center.

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.

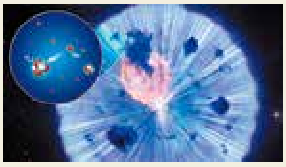
Discovery of many supermassive black holes 13 billion light-years away.

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.

Hot gas from galaxy cluster collisions revealed by multi-wavelength observations.

A team led by Nobuhiro Okabe of Hiroshima University combined Subaru Telescope visible light observations with X-ray and radio data to conduct a detailed investigation of turbulence in galaxy clusters, and found that cluster collisions heat the surrounding gas to more than 400 million degrees.

Composite image of galaxy cluster XLSSC 105. The distributions of dark matter (blue), X-rays (green), and radio waves (red) are overlaid on a Subaru Telescope image of the individual galaxies.
Credit: GBT/NSF/NAOJ/HSC-SSP/ESA/XMM-Newton/XXL survey consortium



Conceptual image of lithium production in nova V5669 Sgr.
Credit: Kyoto Sangyo University

Little lithium produced in classical nova

A team led by Akira Arai at Kyoto Sangyo University used the Subaru Telescope to investigate beryllium, the precursor of lithium, in classical nova V5669 Sgr to investigate production sites of lithium. The amount of lithium produced in this classical nova is only a few precent of that seen in others, indicating a range of lithium production in classical novae.

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

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.

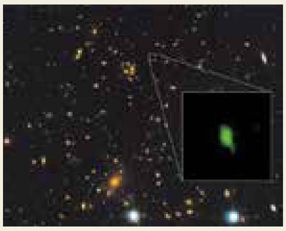
A CCD camera mounted on the telescope for tracking space debris.
Credit: JAXA

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



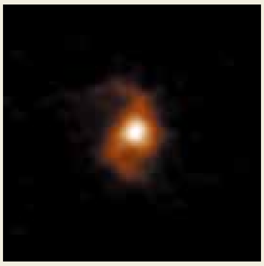
False color image of MACS1149-JD1, a galaxy located 13.28 billion light-years away. The oxygen distribution is shown in green.
Credit: ALMA (ESO/NAOJ/NRAO), NASA/ ESA Hubble Space Telescope, W. Zheng (JHU), M. Postman (STScI), the CLASH Team, Hashimoto et al.

Oxygen in galaxies more than 13 billion light-years away

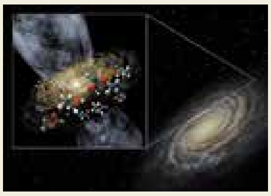
A research team led by Akio Inoue at Osaka Sangyo University used ALMA to detect oxygen in a distant galaxy 13.1 billion light-years away, and then in a more distant one 13.28 billion light-years away. With these discoveries, the record for the most distant galaxy with oxygen was broken twice. These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

Most ancient galaxy with observed spirals

A team led by Takafumi Tsukui, a graduate student at SOKENDAI, found a galaxy with spiral morphology from ALMA data for 12.4 billion years ago. The discovery of a spiral galaxy only 1.4 billion years after the Big Bang could help answer longstanding questions in astronomy about how the shape of a galaxy is determined.



BRI 1335-0417, a galaxy with spirals 12.4 billion years ago observed by ALMA.
Credit: ALMA (ESO/NAOJ/NRAO), T. Tsukui & S. Iguchi



Conceptual image of organic molecules around a protostar in the extreme outer Galaxy.
Credit: Niigata University

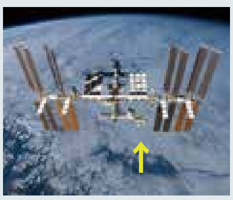
Organic molecules at the edge of the Galaxy

A team led by associate professor Takashi Shimonishi at Niigata University observed the edge of the Milky Way Galaxy with ALMA and found chemically-rich molecular gas including complex organic molecules around a newborn star. The ancient environment is preserved in the extreme outer Galaxy, indicating that organic molecules can be formed efficiently even in the primordial environment.

astronomy" that we 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.

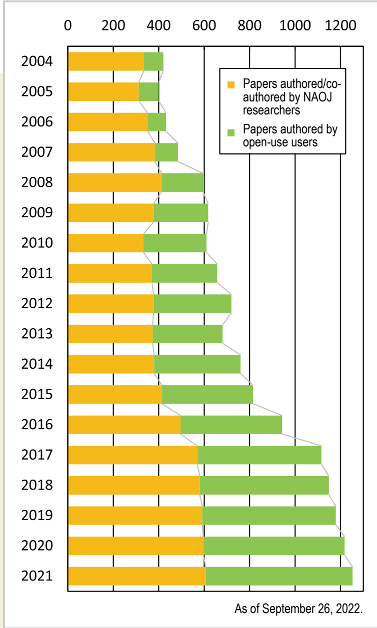


SMILES installed on the Japanese Kibo module. Credit: NASA

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: 2.5 % Percentage of international coauthorship: 79.6 % (2017 ~ 2021 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 is a graduate university based on world class research institutions including NAOJ.

❷ Cooperative Graduate School Program

❸ Visiting Graduate Students Program

Number of Graduate Students (as of April 1, 2022)

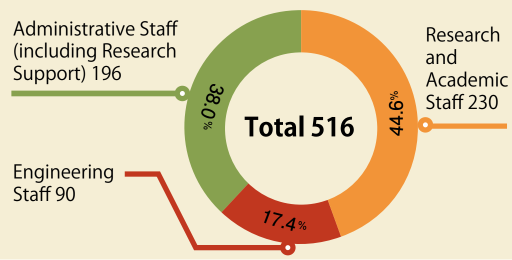
Students from SOKENDAI (five-year doctoral course) 32
Students from cooperative graduate schools......28
Visiting graduate students......14

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

Tohoku University, Ibaraki University, University of Tsukuba, The University of Tokyo, Tokyo Institute of Technology, University of Electro-Communications, Niigata University, Shinshu University, Nagoya University, Yamaguchi University, Kyushu University, Kagoshima University, Osaka Prefecture University, Kyoto Sangyo University, Tokyo City University, Nihon University, Japan Women's University, Hosei University, Tufts University (in no particular order)

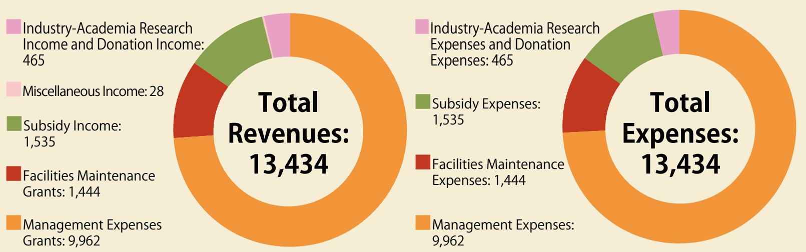
Profile of NAOJ

■ **Number of Employee** (as of April 1, 2022)



■ **Budget** (FY 2021)

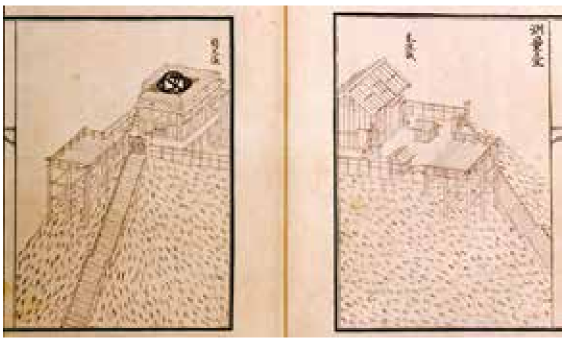
Unit: 1 million yen



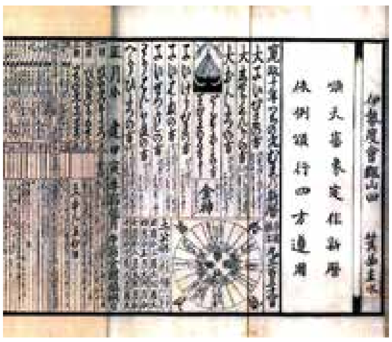
History of NAOJ

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

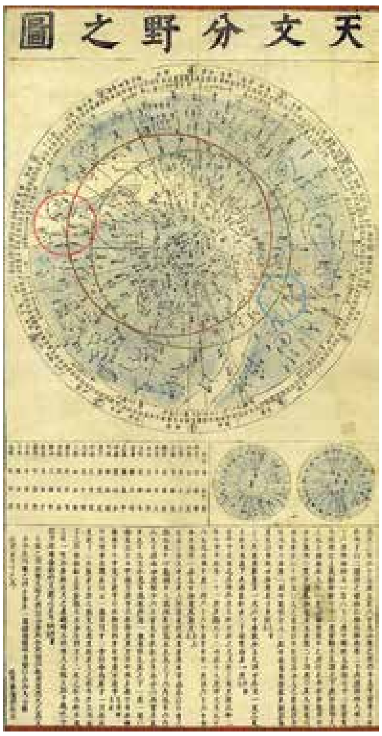
The origin of NAOJ dates back to the late Edo Era (more than 300 years ago) when the Shogunate Tenmonkata started observations of celestial objects to create ephemerides. NAOJ still carries on the compilation of ephemerides as a part of its duties. The Meiji Era saw the inflow of knowledge about modern 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. (Iikura, Azabu)

1899 The Latitude Observatory was established in Mizusawa.

1924 The Mitaka campus was started to establish.

1925 Publication of “Chronological Scientific Tables (Rika Nenpyo)“ began.

Rika Nenpyo

Since its first publication in 1925, we have been publishing Rika Nenpyo for almost 100 years in cooperation with many other research organizations. Also available in English. https://official.rikanenpyo.jp/posts/5905

Mitaka Campus in the early Showa Era

65-cm Refractor Telescope

Laser Interferometer Gravitational Wave Antenna (TAMA300)

Mizusawa 20-m Radio Telescope

ALMA

1926 65-cm Telescope Dome completed.

1929 65-cm equatorial telescope was equipped.

1930 Solar Tower Telescope (The Einstein Tower) was built.

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

1949 Norikura Solar Observatory began observations.

1960 Okayama Astrophysical Observatory began observations.

1962 Dodaira Observatory began observations.

1969 Nobeyama Solar Observatory began observations.

1982 Nobeyama 45-m Radio Telescope began observations.

1988 The National Astronomical Observatory of Japan was established.

1992 Nobeyama Radioheliograph began observations.

1999 Subaru Telescope first light.

1999 Laser Interferometer Gravitational Wave Antenna “TAMA300“ began observations.

2000 Dodaira Observatory was closed.

2000 Visitors’ Area opened at Mitaka Campus.

2001 Agreement of ALMA project among Europe, the United States, and Japan.

2001 VERA Stations began observations.

2004 NAOJ was incorporated as the National Astronomical Observatory of Japan, National Institutes of Natural Sciences, Inter-University Research Institute Corporation.

2006 Ishigakijima Astronomical Observatory began observations.

2006 HINODE began solar observations.

2007 As a part of the Four-Dimensional Digital Universe (4D2U) project, the 3-dimensional dome theater was completed.

2007 The Lunar Explore “KAGUYA” was launched and began observations.

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

2011 ALMA Early Science operation started.

2013 Regular ALMA observations started.

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

2015 Nobeyama Solar Observatory was closed.

2018 Okayama Astrophysical Observatory was closed.

2018 Super Computer ATERUI II started operation.

2020 KAGRA began observations.

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 Hawai‘i. Although this year marks 24 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 and serves as 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.

NAOJ Director General

Dr. Saku Tsuneta

NAOJ

Inter-University Research Institute Corporation
National Institutes of Natural Sciences

National Astronomical Observatory of Japan

2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan
Phone +81-422-34-3600
https://www.nao.ac.jp/en/