The Impact of the NASA – Keck Observatory Partnership

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W. M. Keck Observatory twin Keck Telescopes on Maunakea, Hawaii. (Photo Credit: WMKO Observatory Archive)

Abstract

In the last thirty years, NASA Space Sciences and the W. M. Keck Observatory have established a partnership that has enabled both organizations to collaborate on scientific endeavors, some more successful than others. This ad-hoc relationship started with NASA participation in the Keck II construction around 1993 and it was formalized later in 1996 in the form of a Cooperative Agreement, a contractual vehicle which remains active until the present.

The intention of documenting this partnership is to celebrate 30-years of Keck operations and for the benefit of future similar endeavors that could be established on protected lands. The value of lessons learned from these partnerships enables more effective ways to continue with future partnerships and agreements.

In this document, we present the inception, evolution, and current status of this partnership by exploring four important past and current tasks or activities: Keck II development, Keck Interferometer and Outriggers, Keck Observatory Archive, and the continuous support of NASA space missions throughout the years. After diving into this sensitive and important topic, we offer some reflections on important points of the partnership and identify lessons that can be utilized in the future.

Key Words:

NASA

W. M. Keck Observatory

Maunakea

University of Hawaii

Astronomy

"To advance the frontiers of astronomy and share our discoveries, inspiring the imagination of all."

– Mission of the W. M. Keck Observatory

"Exploring secrets of the universe for the benefit of all."

– Vision of NASA

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1. Introduction

National Aeronautics and Space Administration (NASA) astrophysical sciences, although primarily focused on space platforms, use ground-based observations to complement space research by characterizing, confirming, and observing at different times and wavelengths. Furthermore, ground-based facilities enable testing new technologies, as well as provide input catalogs by making space observations more effective and valuable. This symbiotic relationship has existed for decades and has proved to be an effective way to advance complex research topics that demand all resources available in astrophysics and planetary sciences. NASA and other organizations benefit through partnerships such as this one, especially with advancing science goals and from the research and development of new technologies.

NASA and the National Science Foundation (NSF) have had a successful and long-standing relationship in support of both institutions' efforts to further research and understanding in space, Earth, biological, and physical science activities. NASA's ongoing programs often motivate science objectives, complement, and extend those undertaken through NSF support, while NSF-supported projects also benefit from activities underway at NASA. Additionally, NASA and NSF have established a partnership to support community exoplanet research, the NASA-NSF Exoplanet Observational Research Program (NN-Explore). NN-Explore was created in response to the community need for observational resources for exoplanet discovery and characterization. This partnership continues to support a broad category of science activities which are mutually beneficial for both entities. While NASA primarily focuses on space platforms, the NSF focuses on ground-based platforms, making this a fruitful and complementary partnership.

2. Motivation

Ground-based observatories first opened the window to the cosmos and have continued to provide advancements that have led to many discoveries. The biggest challenges for research from the ground are restrictive sky coverage, the weather, and the atmosphere, which can cause blurring in images as well as block light from certain parts of the electromagnetic spectrum. These issues make the location for these observatories and telescopes critical, and why space-based telescopes are necessary for furthering our understanding of the origins and evolution of the Universe. Many ground-based observatories are in areas of high altitude to minimize the effect of the atmosphere on observations. Among the many locations that are home to major telescopes and observatories, one site that has become known as one of the world's premier sites for astronomy research is Maunakea*.

The University of Hawaii Institute for Astronomy (IfA) was founded in 1967 to carry out research in astrophysics and planetary science, which is continued today. In November 1967, the Board of Land and Natural Resources (BLNR) recognized the importance of Maunakea for astronomy and approved a lease to start on January 1, 1968, with the University of Hawaii (UH) for all lands above 12,000 ft elevation of Maunakea, which is known as the "Mauna Kea Science Reserve" (MKSR). The UH lease is a master lease with the state for use of the land. The lease was signed for 65-years, set to expire at the end of 2033 when the lease will be terminated. New leases will be needed to operate beyond 2033. The broad responsibilities of UH for the summit stem from this lease and included the maintenance of the premises, the right to develop improvements with approval, general liability, and compliance with Department of Land and Natural Resources (DLNR) regulations and other laws [1]. However, the concern of a new lease agreement is now in the hands of the new Maunakea Stewardship Oversight Authority (MKSOA), governing body appointed since July 2022 by David Ige, Hawaii's Governor.

Maunakea is a dormant volcano on the island of Hawaii and is now the site of several major telescopes. The name Maunakea translates to "White Mountain" but is also known in native traditions and prayers as Mauna a Wākea (Kea), "The Mountain of Wākea". The site has become one of the most important in the world and in the northern hemisphere, because of the favorable observing conditions. The summit of Maunakea is located in the most southern part of the United States at latitude 19.8 degrees N and at an altitude of nearly 14,000 ft. It has the best combination of properties needed for astronomy, including low humidity, dark skies, and smooth airflow upward due to location and the shape of the volcano. Furthermore, Maunakea is a historic and cultural landscape that is sacred to many Polynesian cultures for a multitude of reasons.

In the Hawaiian world view, natural and cultural resources are treated alike, the well-being of one depending upon the well-being of the other. Expressions of native beliefs, customs, practices, and history are found in Hawaiian *moʻolelo* (traditions and historical narratives). Through these *moʻolelo*, we can perceive that in the traditional-cultural context, natural resources are valued as cultural properties and it is this cultural attachment to the natural world and the heavens above that defines and shapes the beliefs, traditional cultural properties, and cultural practices of Hawaiians [2]. Native Hawaiians place major spiritual and religious significance to Maunakea, as it is seen as the domain of the gods. This belief makes the summit a highly significant and sacred place.[1] The mountain includes burial sites, ceremonial sites, shrines, archeological sites, trail systems, and buildings. In addition to the cultural resources, Maunakea is home to unique species and habitats. The alpine and subalpine environments that lie below the summit are home to flora and fauna that you can't find anywhere else. Along the trail systems, you'll find ferns and shrubs, trees and native grasses, and over 21 lichen and moss species. If you look closely, you can find several native bird species, the Hawaiian hoary bat, and 35-40 different species of arthropods (including bugs, moths, beetles, spiders, louse, and centipedes).

Maunakea Summit before development. (credit: W. M. Keck Observatory Archives, prior to 1960s)

3. Astronomy on Maunakea

Prior to the arrival of the first Europeans in 1778, the Native Hawaiian people lived in a highly organized and self-sufficient social system with sophisticated language, culture, and

[1] For a more in-depth collection of Native Traditions surrounding Maunakea, see reference [2]

religion. A unified monarchical government of the Hawaiian Islands was established in 1810 under Kamehameha I (the first King of Hawaii), and from 1826 until 1893, the United States recognized the independence of the Hawaiian Kingdom, extending full and complete diplomatic recognition to the Hawaiian Government and entering into treaties and conventions with the Hawaiian monarchs. In 1893, John L. Stevens (United States Minister at the time) conspired with a small group to illegally overthrow the indigenous and lawful Government of Hawaii. Stevens and the naval representatives caused armed naval forces of the U.S. to invade the nation and position themselves near the Hawaiian Government buildings to intimidate Queen Liliuokalani [3]. When informed of the risk of bloodshed with resistance, Queen Liliuokalani yielded her authority to the United States Government. In 1898, as a consequence of the Spanish-American War and through the signing of the Newlands Joint Resolution, Hawaii was adjoined to the United States as a territory without the consent of or compensation to the Native Hawaiian people or their sovereign government. Hawaii officially became the 50th State of the U.S. on August 21, 1959 [3]. An "Apology Resolution" was adopted in November 1993, on the 100th anniversary of the overthrow of the Hawaiian Kingdom, to offer an apology to Native Hawaiians on behalf of the U.S. for the illegal overthrow [3].

In 1960, agriculture and U.S. federal government spending dominated the economy, and the city of Hilo was the center of economic and government activities on the Island of Hawaii. Hawaii has always been susceptible to tsunamis, as it is in the center of the Pacific Ocean and surrounded by the "ring of fire" [4]. On May 22, 1960, a tsunami was generated off the coast of Chile and spread across the Pacific. The tsunami struck the Hawaiian Islands the day after, but the initial waves were not very significant or destructive. The third wave of the tsunami converted into a bore and caused significant damage in Hilo Bay on the island, where the tsunami killed 61 people and injured 282, all centered in Hilo. Following the tsunami, Hilo was in an economic slump. With the island in economic disarray, the community had to consider more creative and innovative ideas to bring money back into the island. Mitsuo "Mits" Akiyama was the individual most responsible for setting the foundation for Maunakea as an astronomical platform. In 1963, when Mits was the executive secretary of the Hawaii Island Chamber of Commerce, he wrote to many U.S. and Japanese universities and research organizations suggesting the development of Maunakea as an astronomical site in an attempt to boost the Big Island's economy [5]. The only response came from Dr. Gerard P. Kuiper at the University of Arizona's Lunar and Planetary Laboratory.

Dr. Kuiper first initiated a study on the nighttime seeing conditions of Haleakala on Maui but became interested in Maunakea because the peaks stood above the cloud level. Dr. Kuiper approached NASA about funding a telescope to conduct test observations [6]. NASA provided funds for the site-testing telescope which Kuiper and his assistant, Alika Herring, used to determine that Maunakea was the best observing site they had ever experienced. Soon after determining that the seeing conditions were excellent, Maunakea became attractive as an observatory site. There were multiple telescope proposals in competition to utilize the summit, but NASA selected a proposal from the UH in 1965. The proposal came from John Jefferies at UH, asking NASA for $3 million (1965 dollars) for an 88-in telescope [6]. The UH 88-in telescope was the first major construction on Maunakea and was dedicated as the seventh largest optical/infrared telescope in the world in 1970. This telescope and the site development associated with it established Maunakea as an excellent site for ground-based astronomy. The telescope is still operational today as a fully remote observatory. Astronomy is among the oldest of sciences, with earliest records from China and Mesopotamia. Polynesian navigators who sailed the open ocean depended in part on a deep knowledge of the positions and motions of stars, planets and constellations [7]. Astronomy was also of considerable importance with Polynesian religious and calendrical traditions and a few Polynesian monumental alignments of apparent astronomical significance during the latter part of the twentieth century [7].

3.1 Infrared Telescope Facility

The next NASA contract was awarded in 1974 to UH as well, this time to build and operate a three-meter telescope facility on Maunakea. The Infrared Telescope Facility (IRTF) was established in 1979 to obtain observations for NASA in support of planetary exploration missions. More specifically, the initial priority was to support the two deep-space Voyager spacecrafts, which launched in 1977, with their observations of Jupiter's "hot spots" [8]. The IRTF is part of the NASA Planetary Astronomy program (PAST), now called the Solar System Observations Program (SSO), which was established to fund ground-based research on solar system objects.[2] In an agreement between NASA and NSF, NASA funds telescope operations (about $6M per year) while NSF agrees to accept proposals for facility instruments and pay support costs (about $150k per year) for observing programs of interest [9]. IRTF is the only NASA-owned ground-based astronomical telescope. The original price to build the IRTF was $6 million, but a change in facility construction authorizations included an increase of $4 million, to a new total of $10 million for construction of the IRTF [10].

In 2009, IRTF was the only ground-based facility dedicated to planetary science. Today the facility is positioned to make significant contributions to the fields of planetary systems, star and planet formation, and stellar science [9]. Observing time for the facility is open to the entire astronomical community, with 50% of the time reserved for observations of solar system objects and NASA spaceflight mission support, and the remaining 50% reserved for general astrophysics observations. Starting in August of 2002, astronomers have the option of remotely observing with the telescope from anywhere in the world, making the observatory extremely accessible [8]. From 2017 to the present, all data from facility instruments are archived at the Infrared Science Archive at IPAC in Pasadena, California, and are publicly available [9]. The IRTF has also been used for support of NASA space missions. For example, the facility was used to observe Io and Jupiter in support of the Galileo mission. The facility also supported missions like Cassini-Huygens and the Japanese Space Agency's Hayabusa sample return mission, to name a few [11]. Another important NASA mission in connection with IRTF was the airborne SOFIA mission, which retired in 2022. SOFIA and IRTF were highly complementary because together they covered most of the infrared wavelength range, and both had high spectral resolution capabilities that complement much lower spectral resolution instruments on space-based observatories, such as the James Webb Space Telescope (JWST) [9].

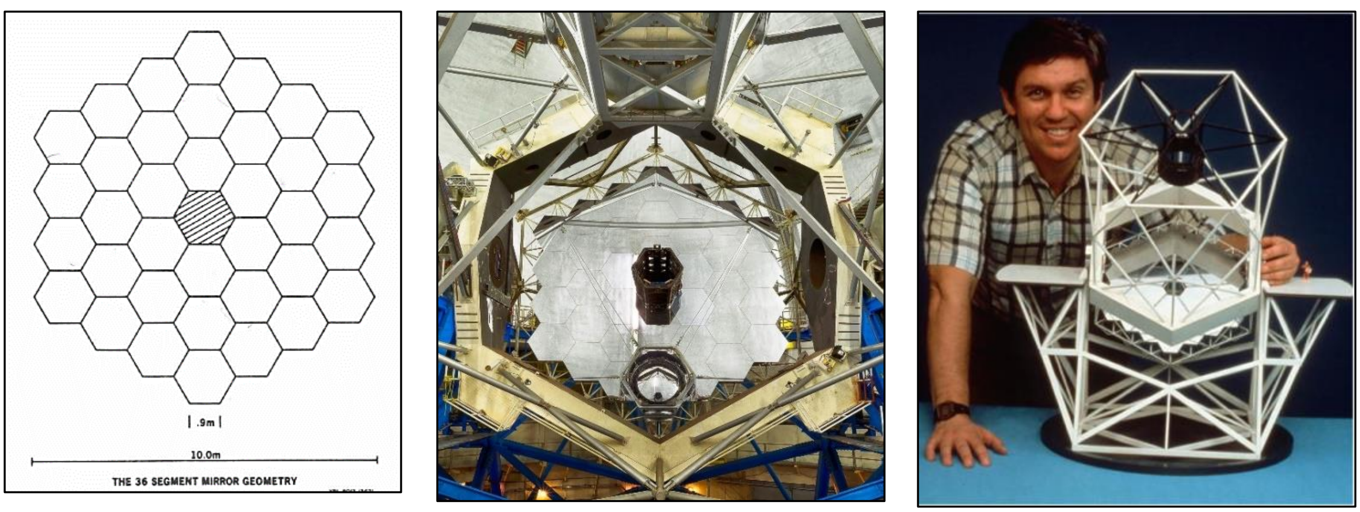
4. W. M. Keck Observatory Early Days

The University of California (UC) system has had a long-term commitment to optical astronomy, starting in 1888 when the Lick Observatory began operations as the first permanently occupied mountain-top observatory in the world. Before the Keck Observatory, the largest optical telescope in the world was the 6-m Soviet Large Altazimuth, which was completed in 1976. Starting in January 1977, UC formed a committee and tasked them with designing a ground-based optical telescope with a 10-m reflecting mirror, which would be the largest optical telescope in the

[2] For additional information about the NASA Planetary Astronomy program, see reference [8]

world. The design task came from a need for larger telescopes with increased collecting area. This is when the concept proposal for a large segmented primary mirror was first started. Jerry Nelson, Terry Mast, and George Gabor presented a design for a large, segmented mirror composed of 36 hexagonal segments in 1979, and the UC committee selected and approved the proposal. The design for the ten-meter telescope became the foundation for the Keck telescope [12]. This design has continued to push boundaries with many of the next generation telescopes being modeled after the Keck segmented primary mirror, including the planned Thirty Meter Telescope, the European Extremely Large Telescope, and the recently launched JWST on December 25, 2021.

Although Nelson is credited as the "Father of the Keck telescope segmented-mirror design", he was not the inventor of the composite-mirror telescope design. There is little to no mention in any related texts of the Italian physicist, Guido Horn d'Arturo, who in 1932 had the idea of using small tessellated (or segmented) mirrors instead of one large mirror as a reflecting surface [13]. D'Arturo began work immediately to construct a 1-m prototype with 80 small trapezoidal mirrors, and in 1935 the first tests were done with the tiled composite mirror. The project was interrupted and delayed by the Second World War, but the major interruptions were caused by the Italian racial laws in 1938.[3] After the war, Guido was able to resume his precious work on the segmented mirror and in 1952, the 1.8-m telescope was completed with 61 segments for the University of Bologna Observatory [13]. The telescope mirror is now relocated to its original seat inside the La Specola (science museum in Italy) in the ancient tower in Florence (Appendix D). Nevertheless, Nelson doesn't credit any historical inspiration. When asked about the segmented mirror design, he stated, *"I guess I came up with it on my own, but it is kind of obvious. Bathroom floors have been segmented for thousands of years"* [14]. He also pointed out the segmented nature of radio astronomy dishes and solar panels.



Left: Design of 10-m primary mirror with 36 segments. (credit: [15]) Middle: Keck mirror assembled. Right: Jerry Nelson "Father of the Keck telescope segmented-mirror design". (credit: Keck Observatory Archives)

As astronomical research expanded in the early 1970s, concerns about future developments on Maunakea were raised by the community and the Native Hawaiians. The number of interested

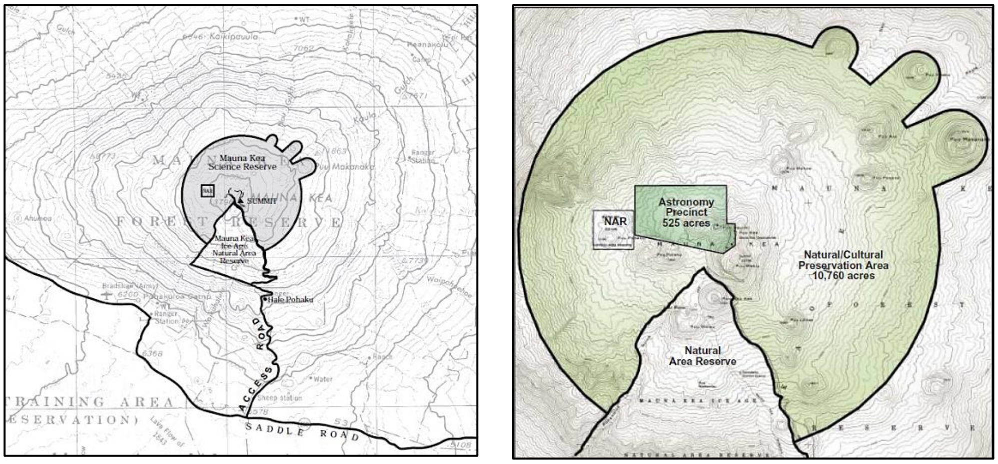
[3] The Italian racial laws, otherwise referred to as the Racial Laws, were a series of laws which were promulgated by the Mussolini government in Fascist Italy (1922–1943) from 1938 to 1943 in order to enforce racial discrimination and segregation in the Kingdom of Italy.

parties who wanted to utilize the summit for astronomical research made it clear that an overall plan was necessary in order to control development on the mountain and provide management guidelines. The UH Board of Regents (BOR) adopted a Research Development Plan (RDP) in January 1982 as the basis for development on Maunakea, and the MKSR Complex Development Plan (CDP) was prepared the next year to provide the guidelines for it [16]. The general purpose of the CDP was to present a management plan and implementation strategy for managing and monitoring the various uses of the mountain. The plan identified three proposed new telescopes, including the Caltech 10-meter submillimeter telescope (CSO), a 15-meter millimeter-wave telescope (JCMT), and a 10-meter optical/infrared telescope (Keck I). The Keck Observatory obtained a sublease with UH for land within the MKSR for construction of the telescope.

Construction for the Keck Observatory was funded in January 1985 when Howard B. Keck and the W. M. Keck Foundation granted $70M (1985 dollars) to Caltech to build the Keck I telescope and the ancillary observatory. Under this agreement, Caltech would use the funds to build the telescope and UC would provide the money to operate it for 25 years. Later that year, UC and Caltech formed the California Association for Research in Astronomy (CARA), a nonprofit corporation incorporated in the state of California, responsible for building and operating the observatory. Ground broke to begin construction that September on Maunakea, and the groundwork was complete with the concrete poured by the summer of 1987. The Keck I telescope dome was completed in October 1988, and construction on the telescope began [17].

Construction of the dome of Keck I on Maunakea summit in 1987. (credit: Keck Observatory Archives)

The CDP of 1983 had guided development on the summit up to the year 2000 and had largely been implemented. Included in the plan were efforts to develop astronomy as an academic field of study with an industrial or technology component, which had been highly successful. After further development on the summit, issues and concerns regarding the use of Native lands were brought to attention by the community on the previous 30 years of development on the mountain. The University of Hawaii BOR adopted a new Master Plan for the MKSR in June 2000, as the new policy for the use of the summit. The Master Plan implemented a new management structure and addressed the plans for community involvement and future development through the year 2020 [1]. Part of this Master Plan included a physical planning guide, which implemented the division of the existing MKSR into two areas: the 10,760-acre Natural/Cultural Preservation Area and the remaining 525-acre designated Astronomy Precinct. The education and research component of the Master Plan included the following proposed actions and developments: expansion and recycling of existing observatory sites, additional sites for new telescopes, and expanded educational outreach.



Mauna Kea Science Reserve area division: Natural/Cultural preservation area and astronomy precinct area mapped out. (credit: [1])

5. NASA Partnership

NASA's Solar System Exploration Division established a Science Working Group (SWG) to formulate a strategy for the discovery and study of other planetary systems in 1988 [18]. The SWG held several meetings in 1988 and 1989 to review prospects for future work, leading to a one-week workshop in January 1990, named "Toward Other Planetary Systems" (TOPS). The TOPS Program was a plan for NASA to determine the answer to the question: Do planetary systems exist around other stars? The program had three main goals: to discover planetary systems, to understand their formation, and to lay the groundwork for a greater challenge. The outcome of this workshop was the formulation of three programmatic phases to help reach the objectives of the program. Phase one (TOPS-0) concentrated on ground-based approaches, centered on the Keck II telescope and the concept for the Keck Interferometer. Phase two (TOPS-1) concentrated on space-based approaches, centered on an orbiting instrument. Phase three (TOPS-2) concentrated on a major instrument that could directly detect Earth-like planets, centered on a technical development program for interferometry [18].

Also in 1990, the Space Studies Board Committee on Planetary and Lunar Exploration (COMPLEX) published a revision of the 1978 report "Strategy for Exploration of the Inner Planets, 1977-1987" that set forth the objectives and overall strategy for the discovery and study of other planetary systems and for the investigation of planet formation. In the revision, the committee modified the report in the form of an update as most of the report was still pertinent. The basic objectives for exploration of the planets as listed in the report were: to determine the present state of the planets and their satellites, to understand the processes active now and at the origin of the solar system, and to understand planetary evolution, including the appearance of life and its relation to the chemical history of the solar system [19]. The report also included a list of recommendations and conclusions for each planet and other relevant topics.

With the recommendations of the COMPLEX committee and the initial TOPS workshop, an ad hoc committee was convened and recommended that NASA seek a partnership with the W. M. Keck Observatory (WMKO; called Keck). This decision led to an intensive study to work out a detailed plan for the TOPS Program and conduct a site visit to Keck. The second TOPS workshop then took place in Hawaii in January 1992, leading to a general plan and the technological requirements for the TOPS program [18]. The COMPLEX and TOPS roadmaps that led to the recommendation for NASA to partner with the WMKO were both conceived before the 1995 detection of the first exoplanet around a main sequence star, 51 Peg b [20]. These NASA efforts were visionary, before the Kepler telescope discovered that planets outnumber stars in the Milky Way Galaxy [21]. Today, the number of confirmed exoplanets amounts to around 5,500 [22].

5.1 Keck II Construction

Even before the construction of the Keck I telescope, there was considerable interest in building a second identical telescope next to it. The combination of the two telescopes could provide the basis for a powerful interferometer, in addition to the collecting power of the two telescopes. After the successful first light images of the Keck I telescope in April 1992, it became clear that the addition of a second telescope would be highly beneficial. The Keck Foundation approved a second major grant of $62 million (1993 dollars), which covered 80% of the construction cost for the Keck II telescope. CARA was responsible for funding the other 20% of construction cost for the telescope through partners. Initially, NASA agreed to pay CARA $44 million for 1/3 of the construction cost for Keck II, but the agreement was not well documented and later converted into a Cooperative Agreement with more specific details. Subsequently after these initial investments, NASA entered into a CA award with Caltech to become a formal partner in CARA for the Keck Observatory Collaboration in September 1994 [23]. The award agreed that NASA would pay 1/6th of operation costs for the Keck Observatory (both Keck I and Keck II) and in return would have access to 1/6th of the available observing time of both telescopes per year. The award amount would start in Fiscal Year (FY) 1995 and was set to last for 72-months. The total award amount was $44 million, equaling roughly $7 million per year. The Keck II telescope saw first light in February 1996 and regular scientific operations began in October of that year.

Adaptive Optics (AO) or corrective optics are used to correct for the blurring caused by the atmospheric turbulence by using a deformable mirror to make ground-based telescopes "see" almost as clearly as if they were in space. AO systems have been used on astronomical telescopes since the early 1990s, but at that time they were only on 3 to 4-meter telescopes. In December 1993, the Keck foundation approved a grant for the development of AO facilities at Keck [24]. The Keck II telescope would become the first large telescope worldwide to develop and install an AO system with a Natural Guide Star (NGS). The first light image obtained with the Keck AO system was in February 1999, dramatically illustrating the capability of the system [25]. The Keck I telescope also integrated the AO system shortly after in 2000. NGS systems still have limitations because they need bright stars to measure the distortions through the Earth's atmosphere, so to increase the limited sky coverage a laser beacon is used to simulate a bright star. This method is known as a Laser Guide Star (LGS) and uses a sodium-wavelength laser. The laser creates an "artificial star" that allows the Keck AO systems to observe 70-80 percent of the targets in the sky, compared to the 1 percent accessible without the laser [26]. The Keck II telescope AO system was designed to be an LGS system, and it was integrated with the telescope in 2001 [27]. The addition of the Keck LGS expanded the range of available targets for study with the twin Keck AO systems.

During the construction of the Keck II telescope, the Subaru Telescope was also being built. The Subaru Telescope is an 8.2-m telescope located on Maunakea and is run by the

National Astronomical Observatory of Japan (NAOJ). In January 1996, there was a fire at the telescope facility, which started with sparks from a welder igniting insulation. The fire smoldered and generated noxious smoke which sent twenty-six workers to the hospital in Hilo and killed three workers[†]. The Keck summit crew were the first responders to the fire until emergency personnel were able to reach the summit facility. After the fire, the Hawaii Employee Assistance Services provided debriefing and counseling services to the Keck employees in need. The EAP Director at the time, Leslie Kissner, oversaw the team sent to Keck as the construction on the observatory continued. Kissner later went on to become the Executive Assistant at Keck in July 2003 and worked there until she recently retired in June 2021. She said that the years she worked at the observatory were *"great years"* and that she was *"proud to have worked and retired from there"* [28]. Being someone who was raised since the age of four on the island, Kissner felt that astronomy was good for Hawaii's economy and that employment of kama'aina (born in Hawaii), including Native Hawaiians, would create more acceptance of astronomy to continue on sacred places like Maunakea. Only about 25% of those working in the Maunakea astronomy community are from local communities and/or are Native Hawaiians, and an increase would result in stronger relationships and greater mutual respect [29].

5.2 Keck Interferometer and Outriggers Project

The two TOPS workshops that took place in 1990 and 1992, respectively, outlined the phases of NASA's TOPS Program. In October 1996, a joint NRC-NASA workshop was held which established the Origins program within the Office of Space Science. The Origins program had a goal of finding and detecting other planetary systems and of understanding the origin of planets, stars, and galaxies [27]. NASA outlined four main goals for the Origins program: 1) to understand how galaxies formed in the early universe, 2) to understand how stars and planetary systems form and evolve, 3) to determine whether habitable or life-bearing planets exist around nearby stars and 4) to understand how life forms and evolves [28]. The ability to meet these goals required use of interferometry, and recommendations to develop a long-baseline interferometer that was optimized to perform a comprehensive planet-detection program came from the Origins program and the TOPS program. The Keck I and Keck II telescope are about 85 meters apart, which was considered a fixed interferometric baseline. The original interferometer concept for the observatory included an additional four movable telescopes, each with a diameter of 1.5 to 2.0 meters (this would later change to fixed position telescopes).

5.2.1 Keck Interferometer

The Keck Interferometer (KI) program was a NASA-funded joint project between JPL and CARA. The overall program was a multi-year coordinated program with three phases, each phase having a specific goal. Phase 1 consisted of site tests, design studies, and applications for permits and equipment. Phase 2 involved linking the two 10-m Keck telescopes (Keck-Keck) as a Michelson interferometer with test telescopes. Phase 3 was the addition of the four outrigger telescopes to the Keck interferometer for imaging. Initial funding for the project began in March 1997 with a CA (NCC7-8) between NASA and CARA, with the purpose of CARA starting work on Phase 1 of the plan [30]. Additional funding was necessary to continue working on the project and NASA awarded another CA (NCC7-9) to CARA for the Keck Interferometer. The contract was multi-year, beginning in FY1999 and was to provide funds to complete the KI program with substantial NASA involvement. The total award amount for the project was $27,835,000 (1999 dollars), split up over 5-years [31]. While the planning for the outrigger telescopes continued, the Keck Interferometer obtained first light in March 2001 and started science observations in June 2002. The KI continued observations with great success, although it never reached the full scientific potential planned. KI ceased operations at the end of 2012 because it had achieved the primary science objectives set forth originally.

During its operation from 2003 to 2012, the KI had been scheduled for a range of peer-reviewed science programs. For example, KI observations have been used to study questions in science topics like stellar astrophysics, young stars and protoplanetary disks, and extra-galactic topics [32]. For example, in 2008 NASA solicited proposals for Key Science teams to use the Keck Interferometer Nuller (KIN) to study exozodiacal dust around main sequence stars. NASA allocated 32 nights of KI time for this Key Project and 42 targets were observed. Missions similar to this one are critical for planning NASA's exoplanet missions. Also, between 2008 and 2011, forty-seven nearby main-sequence stars were surveyed searching for faint resolved emission from exozodiacal dust [33]. Another major science highlight was KI being the first optical/near-infrared interferometer to detect an object outside our own galaxy, detecting Active Galactic Nuclei NGC 4151. NASA's primary goal in developing the KI was the characterization of faint dust disks around nearby stars, which was accomplished with the nulling observational mode and a Key Science program, leading to the eventual shutdown at the end of 2012. There are 51 refereed scientific publications that came from research using the KI [34].

5.2.2 Outrigger Telescopes

This portion of the KI project (Phase 3) was described extensively in the October 1997 document "*Outrigger Telescope Project Description*" [35]. The Outrigger Telescope project (OTP) was a key element in NASA's Origins program. NASA had previously defined six specific ground-based interferometry objectives to help achieve the Origins program goals. Two of these goals were achievable with the interferometer alone, three required combining the interferometer with the outrigger telescopes, and one required only the outrigger telescopes. Combining the Kecks with the outriggers is referred to as interferometric imaging, where they would form a *"sparse array with the relative locations of the telescopes chosen to maximize the 'uv-plane', or spatial-frequency, coverage"* [35]. Plainly put, the outrigger telescopes would be used to get starlight into the interferometer, and the interferometer would be used to collect the data.

The State Draft Environmental Assessment (DEA) for the OTP was prepared by the UH IfA and filed with the State Office of Environmental Quality Control (OEQC) in March 1999 and circulated for public review. NASA's DEA for the project was completed and made available in December 2000 for review by Federal and State agencies [36]. In early 2001, UH IfA submitted a Conservation District Use Permit (CDUP) application to the BLNR for the construction of the outrigger telescopes. The proposed land use required an approved management plan, and the Board determined the proposed management plan was inadequate, putting a hold on the permit. During the review period for the DEA, a Construction Best Management Practices Plan (CMP) was reported for the Outrigger project. The CMP specified the methods and controls which would be implemented to prevent or minimize negative impacts to the surrounding environment, and to the natural and cultural resources on and adjacent to the WMKO site during construction. The concerns included in the plan were the Wekiu bug population, the historic district and potential burial sites, the views planes, waste control, and toxic/hazardous waste [37].

After comments, concerns, and meetings over the review period, the final EA was released to the public in February 2002. The company contracted to design, fabricate, and ship via sea transport the four Outrigger Observatory domes was Electro Optic Systems (EOS) Pty Limited, located in Australia. The contract was signed in August 1999, with a fixed total price of $2,123,700 for the Outrigger observatories. The contractor EOS is the parent company of EOS Technologies (EOST) in Arizona. At the time of this contract, EOST was already under a separate contract with CARA to design, fabricate, assemble, test, and deliver four Outrigger Telescopes for the KI program. In April 2002, shortly after the release of the final EA from NASA, the Office of Hawaiian Affairs (OHA) filed suit against NASA and UH to prevent the building of the outrigger telescopes (Appendix B.1). The final EA was deemed inadequate by OHA, and they directed NASA to prepare a new EA that addresses cumulative impacts (i.e., accounting for every construction and occupation made on Maunakea since the early 1960s). There were many other reasons for this suit including both environmental and cultural concerns, specifically regarding the continued use of Maunakea. Concerns that a new EA would be challenged in court once again, NASA decided to conduct a full Environmental Impact Statement (EIS).

Carl Pilcher, former Program Executive & Scientist in the Astronomy and Physics Division at NASA, oversaw and led the EIS process for the OTP. He was also the first official NASA Liaison for the CARA Board of Directors, which granted him access to the board meetings but with a non-voting status. The non-voting status of this position is because NASA, as a federal agency, by law is forbidden to influence and participate in the management of a state incorporated institution, such as CARA. With Pilcher, a small team and a contractor group were utilized to work on the EIS. Among these teams were specialists in environmental compliances and a background on NEPA laws. The process took approximately three years, and during this time this team traveled to Hawaii every three months for meetings and to work on the EIS. After two years of working on the document, the Notice of Availability (NOA) for the Draft EIS was published by NASA in July 2004. There was a public comment period from August to September, and the comments were addressed in the Final EIS. With the Draft EIS published, and the management plan approved by BLNR, the CDUP application for the building of the Outrigger telescopes was granted in October 2004. This decision was not widely accepted, and a month later another lawsuit was filed, this time to appeal the state's permit approval (Appendix B.2).

The final EIS was released in February 2005 and addressed all previous concerns as well as the cumulative impacts of everything that had been built on Maunakea since the beginning of telescope and facilities construction in the 1960s. NASA paid a great deal of attention to both process and content in preparing the EIS and believed that it would withstand a court challenge, and it was in fact never challenged. The EIS was considered a major success by NASA, and even by members of the Hawaiian community. NASA was convinced that having completed the first federal EIS for a telescope project on Maunakea would help lay the groundwork for future projects, particularly the Thirty Meter Telescope (TMT). Letters were received from the State of Hawaii OHA Board of Trustees and United States Senator Daniel Inouye expressing appreciation to the NASA team for managing the

EIS process professionally and considering a great respect to the Hawaiian community, showing mindfulness to the strong cultural tie to Maunakea. The Native Hawaiians who were opposed to any further building on Maunakea felt that the cumulative impacts of astronomy were not addressed properly and could not be undone. Those opposed continued to express their views on Maunakea being utilized for astronomical purposes and not being respected as the sacred land it is. Although the EIS was regarded as successful, the protests and lawsuits played a large role in the delays of the project, putting off the project for multiple years.

Due to these delays and associated budget issues, the funding for the Outriggers was cut in the NASA's FY07 President's Budget Request in February 2006. The budget specified that the project will not pursue the telescopes in order to focus on meeting primary nulling requirements for KI. The two primary KI science objectives could be met without the additional Outrigger telescopes, but the other four science objectives would no longer be achievable. Delays and budget influenced the decision to terminate the project, but they weren't the only factors. Another driving factor in the rushed process to complete the OTP was the importance of combining the telescopes with the KI to achieve new imaging modes, but after the extended period of delays, the ESO had already implemented similar imaging modes.

On September 1, 2006, one of us (RJH), then Acting Director of the Astrophysics Division at NASA, sent a letter to the U.S. Naval Observatory (USNO) discussing an opportunity for partnership regarding the Outrigger telescopes. Although a response was returned by USNO, negotiations continued for the next 2 ½ years. CARA sent an official letter to the U.S Department of the Navy on January 16, 2009, offering a gift of the Outrigger telescopes and their respective equipment for the USNO. In November 2010, the Department of the Navy accepted the gift offer from CARA for the four telescopes. Although plans to incorporate them into the Navy Precision Optical Interferometer (NPOI) in Flagstaff, AZ were made, an update from 2017 showed that the outriggers were no longer available for use with the interferometer. At this point, the telescopes have not been utilized at any facility.

5.3 Keck Observatory Archive

Astronomical data have been archived for millennia, with the earliest documented records dating back to the Babylonians. More recently, many astronomy archives have been created and utilized since the 1960s, providing access to data from missions and projects to the science community and the public. Archives serve as a resource for scientists, students, and the public to utilize for both new research and understanding old research. The NASA Space Science Data Coordinated Archive (NSSDCA) was NASA's first archive and was established at Goddard Space Flight Center in 1966. The NSSDCA served as a permanent archive for NASA Space Science mission data and space physics mission data.

The Keck Observatory Archive (KOA) is a joint collaboration between the WMKO and NASA Exoplanet Science Institute (NExScI) and is funded by NASA as part of the Exoplanet Program Office at JPL. The physical location of the archives is run by NExScI. KOA was commissioned initially in 2002 for NASA-acquired, level-0 (uncalibrated) scientific and calibration data from the High-Resolution Echelle Spectrograph (HIRES) instrument located at Keck. The archive moved from the design and development phase to an operational system in August 2004, becoming open to accept HIRES data for ingestion. The aim of KOA was to 1) promote the NASA Navigator Program goal of searching for extra-solar planets, 2) curate and disseminate observations made on Keck Single Aperture instruments to maximize science return from the observatory, and 3) enable long-term instrument performance studies that would benefit development of observing programs.

The decision was made to expand the archive to include all HIRES data, not just the NASA-acquired data, and an agreement was made in May 2005 [38]. The agreement was signed by Anne Kinney, then Director of Universe Division (now Astrophysics Division) at NASA Headquarters. By agreement with partners Caltech, the University of California, the University of Hawaii, the National Optical Astronomy Observatory, and JPL, KOA expanded to make science data open to the public. After the agreement, the archive expanded to include all additional instruments that have acquired data over the lifetime of WMKO, not just the HIRES instrument, and for all community users and not only for NASA users. KOA officially opened for business to the public in July 2006 and has been providing access to the WMKO data ever since. The data provided by KOA has been utilized by many observers/scientists, with the number of citation rates growing each year (Fig 1). Research papers citing the use of KOA cover fields such as the structure of the intergalactic medium, stellar evolution through studies of stellar abundances and ages, and spectroscopic and imaging searches for exoplanets and faint stellar companions [39].

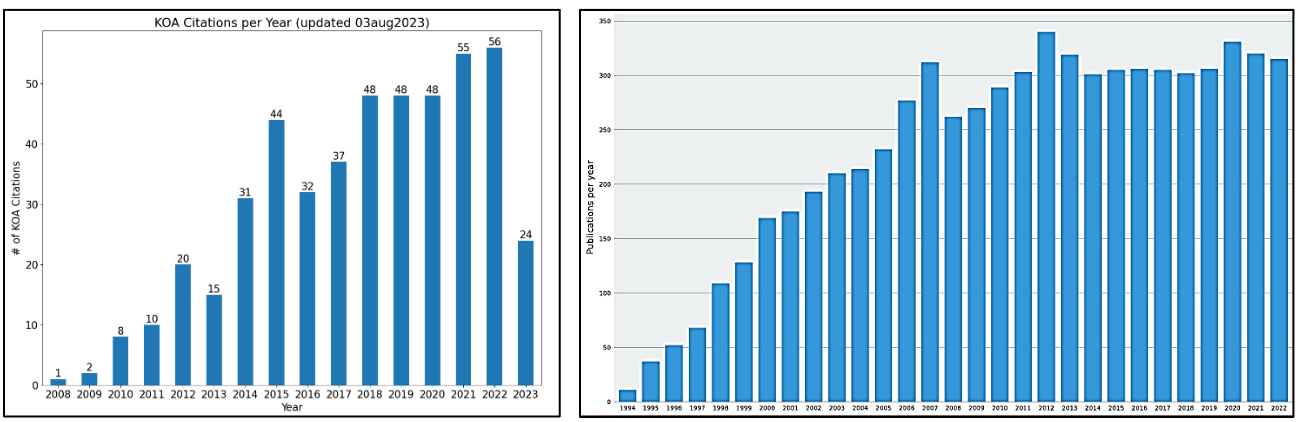


Figure 1: (Left) Cumulative number of refereed papers that cite the Keck Observatory Archive from 2008 to May 3, 2023. (Right) Cumulative number of papers that cite the Keck Observatory from 1994 (credit: Dawn Gelino)

In 2015, Kinney and the KOA team (full list of names provided in [40]) earned the NASA Group Achievement award. The award was nominated by Paul Hertz and Mario Perez of NASA *"for 10 years of pioneering achievements that increase the impact of Keck data and establish a model of all observatories*." The award nomination letter states that "*the NASA KOA team has boosted the science value of data acquired at WMKO by providing the scientific community with open and unparalleled access to WMKO data*" [40]. KOA continues to provide open data 12-18 months after the proprietary period from all observations. The extensive amount of data that is publicly available in KOA has created a dynamic system of innovative research and new data products. The data in KOA is not always easy to use for researchers, so the Keck Observatory is utilizing a new program called the Data Services Initiative (DSI) to modernize the data flow and increase scientific yield. The DSI will transform the end-to-end data flow of data delivered to Keck observers and the community at large through the Keck Observatory Archive (KOA), providing both raw and science-ready data during the night.

5.4 Supporting Space Missions

NASA's portion of the Keck observing time (1/6th share) is managed by NExScI, where proposals are open to the entire U.S. astronomical community. NASA' access to Keck time, which is nationally competed, is primarily utilized in support of on-going missions and/or high priority, long term science goals. NExScI is a science operations and analysis service organization for NASA Exoplanet Exploration Program projects. Proposals will be evaluated to determine if they meet the long-term science goals outlined in the SMD science plan and are within a specific science area. Among these science areas are Exoplanet Exploration (ExEP), Cosmic Origins (COR), Physics of the Cosmos (PCOS), and Planetary Science (PS), and others [41]. Three types of proposals are accepted for observing time: General Observing (GO) time, Key Strategic Mission Support (KSMS) time, and Mission Support time. GO proposals can be among any of the given science areas. KSMS proposals must directly support NASA space missions and science goals, and the projects can support past, present, and/or future missions. Mission Support proposals are GO proposals that meet mission support criteria for confirmed and operating NASA space missions only.

For decades, Keck has provided data for exoplanet researchers as well as planetary and solar scientists studying celestial objects in our own solar system, and the data informs numerous studies supported by the NASA Astrobiology Program, too [42]. From 1996 to 2008, the use of NASA-Keck time was allocated to support the following areas: detection of extrasolar planets, origin and nature of planetary systems, investigations of our own solar system, and direct mission support [43]. In 2009, NASA HQ added all COR science including stars, star formation, galaxies/AGN, and galaxy formation to the approved list of science topics. Since 2018, there have been over 1000 proposals submitted under NASA-Keck time that mention space missions (Appendix E). Of those proposals, a little under 400 were selected to complete observations, showing just how competitive it is to apply for time. Keck has been critical in supporting a variety of astrophysics and planetary space missions. A non-exhaustive list includes missions such as Cassini, Juno, Hubble Space Telescope (HST), New Horizons, SOFIA, Kepler, and now James Webb Space Telescope (JWST) [44]. Further support for Euclid, TESS, Europa Clipper, and Roman Space Telescope (RST) will come from the observatory as well (reference Fig 2 for space missions separated by NASA division).

One of the more notable collaborations is between Keck and Hubble. The two started observing around the same time and many assumed they would be competitors, but the data from both proved to be complementary and very productive. For example, in 2007 a team of astronomers reported observations of the Uranus system as it approached its equinox, which happens once every 42 years. Extensive observations were made between 2001-2007 using Keck and during 2003-2007 using the Hubble telescope. The observations showed that the rings of Uranus had changed significantly since their discovery in 1977 [45]. Another achievement that came from this partnership was in 2018 when a team of researchers reported a survey of hundreds of nearby galaxies using imagery from Keck and Hubble. The results suggested that more than 17 percent of the targeted galaxies host a pair of black holes at their center [46].

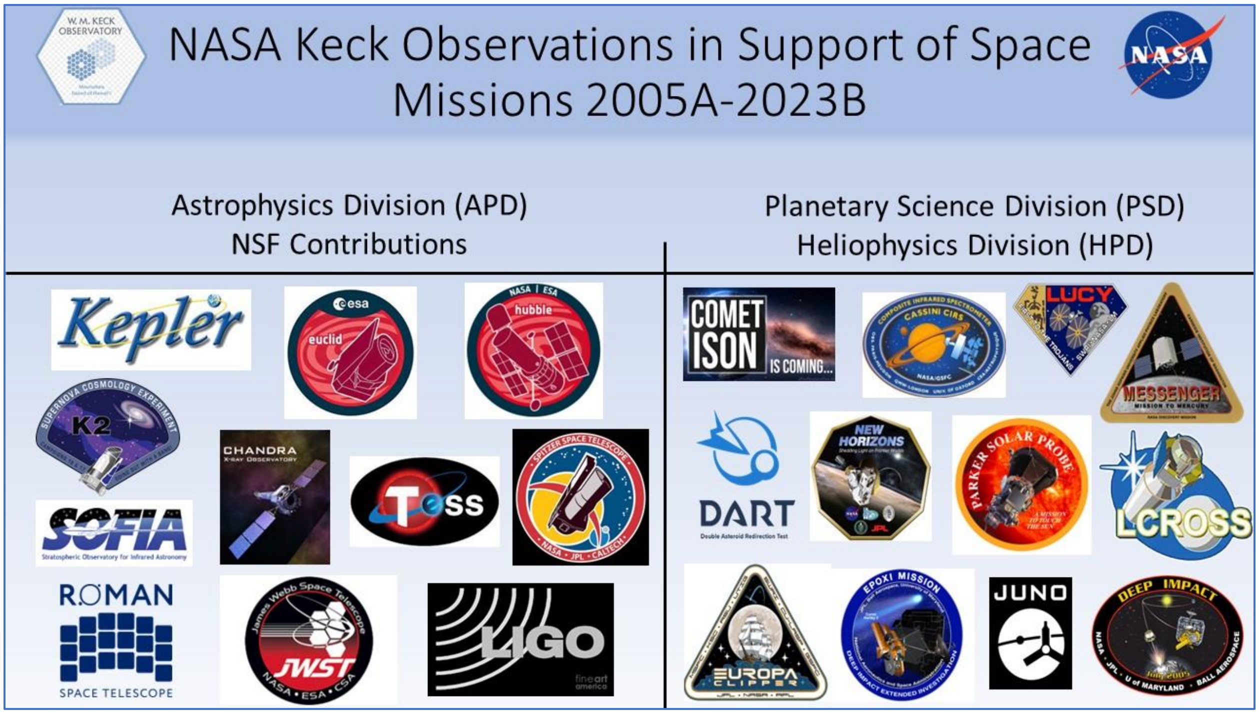


Figure 2: Space mission support from NASA through Keck partnership (credit: one of us (CNL) and [58])

Another productive partnership came from NASA's Kepler space telescope and Keck, after tag-teaming to verify the largest collection of exoplanets ever discovered. This led to a census of extrasolar planets with data so detailed that demographics of Earth-sized planets are included. A new type of space-ground hybrid observatory, the Orbiting Configurable Artificial Star (ORCAS) mission is also working with Keck to provide Great Observatory quality capabilities open to all US observers via a community driven observation plan at a lower cost. By enabling AO and flux calibration observations, ORCAS will deliver highly detailed images, with the ability to detect a population of supermassive black hole binaries for the first time, among many other advances [47]. To support the ORCAS mission, the ORCAS Keck Instrument Demonstrator (ORKID) was built and delivered as an early performance demonstration with the Keck II AO system. ORKID has been designed for four main primary science groups: Solar System, Binary Stars, Accreting Exoplanets, and Active Galactic Nuclei [47].

Perhaps the most anticipated collaboration is that between the JWST and Keck. In October 2022, astronomers tag-teamed to capture a set of images that revealed large clouds in the northern hemisphere of Saturn's largest moon, Titan. The JWST team used the Near-Infrared Camera (NIRCam) to observe Titan during the first week of November, and after seeing the clouds they immediately contacted the Keck Observing Team to request follow-up observations. The Keck team used the second generation Near-Infrared Camera (NIRC2) in combination with the Keck II AO system to track the clouds' motions on Titan [48]. The Cosmic Evolution Early Release Science Survey (CEERS) project was funded in 2017 as part of NASA's Early Release Science Program, selected to use JWST during its first five months of operation. The goal of the CEERS project is to demonstrate efficient JWST parallel survey exploration of the high-redshift universe, by overlapping parallel observations with the JWST instrument suite. Prior to the launch of JWST, only the most massive black holes at high redshifts could be identified, but the spectroscopic capabilities of JWST now enable the search for signs of AGN activity from less luminous sources [49]. The CEERS team reported the discovery of an accreting supermassive black hole at z = 8.679, the galaxy (CEERS_1019) being previously discovered as a Lyα-break galaxy by Hubble with a Lyα redshift from Keck [49]. These examples are just a small glimpse into how Keck will continue to support space missions in not just astrophysics, but planetary sciences and heliophysics as well.

6. Reflections and Lessons Identified

After diving into this sensitive and important topic by reviewing public and private documents as well as interviewing people associated with these activities, we offer some reflections on three important points of the partnership and identify lessons that could be utilized for future projects. It is important to acknowledge that no Native Hawaiians were interviewed for this project and spending the time to deeply understand the indigenous peoples' perspectives is essential when developing projects on Native Lands. The documentation of this partnership is vital now, not only because it will become more difficult over time as records get dispersed, data degrades, and the collective individual memories fade with time, but because understanding the successes, challenges, and impacts of any partnership helps to inform future program managers on best practices and management strategies. Here we provide an overview of the successes of the partnership as well as touch on the parts that are considered less successful, discuss the use of Native lands for projects and ways to create better collaboration for the partners, and review the management system for complex facilities with an emphasis on moving toward a model of mutual stewardship.

6.1 Successes of the Partnership

The successful private-public partnership that has supported Keck contributed by university, philanthropy, and government funding (NASA and the NSF) has created a dynamic and sustainable management system for the institution. The observatory functions as a 501(c)3 non-profit research organization with Caltech, UC, and NASA being partners in operation. When discussing the management system, the dynamic of the team was often highlighted. The observatory in terms of project management practices works well, with structure and timelines for getting tasks to completion on the technical side and focus on making the project operational on the other. James Fanson, project manager on the KI project from 2003-2006, told us *"there was not a lot of tension between the partners during the project, even though the management practices were different among them"* [46]. The different practices from each partner come together to create a system of management that has worked for over a decade, but the addition of new practices and perspectives may create a more collaborative system.

This study of historical, current, and future developments at Keck has revealed a steady commitment to scientific achievement and a philosophy of innovation. The achievements of Keck have been pioneering. "*Over the years, both telescopes peered at a host of astronomical objects. Faint supernova. Stellar wobbles. The oldest-known quasars. Analyzing these observations profoundly altered astronomers' views of the universe"* [14]. The mission of Keck is to advance the frontiers of astronomy and share our discoveries, inspiring the imagination of all. Among those discoveries, "*They* [astronomers] *have learned that the universe is accelerating; extra-solar planets reside in the Milky Way; and heavy hydrogen atoms thrived during the Big Bang"* [14]. There have also been both successful and less successful non-scientific endeavors with this partnership between NASA and the WMKO, and both have provided insights into how the future of these partnerships should continue. The Keck Interferometer is considered successful with major technical achievements stemming from the science data, although the science was limited by time online and the unplanned cancellation of the OTP. The cancellation of the OTP stemmed from long-standing issues and grievances with the use of Maunakea but has led to new management and a new sense of understanding among program planners. The Keck Observatory Archive has been highly successful by providing the scientific community with open access to all WMKO data, which is now the model for all observatories.

The future of the observatory and the partnerships it brings depend on collaboration and a model of mutual stewardship. Mutual stewardship is about coming up with solutions that benefit the whole among people with different perspectives, based on trusting relationships. The Hawaiian culture encompasses ‘ohana, which is a central concept representing extended family and community support, making the traditional way of doing things on the mainland U.S. much different and therefore not sufficient when working with the Hawaiian community. Becoming part of the family and incorporating the concept of ‘ohana into the decisions made on Native lands can build a solid relationship that is respectful and considerate. In the Decadal Survey on Astronomy and Astrophysics (Astro2020), there is substantial focus on engagement with local and Indigenous communities for the 2020s and beyond. There is a section specific to the astronomy on Maunakea and the recommendation moving forward is for the astronomy community to define a “*Community Astronomy model of engagement that advances scientific research while respecting, empowering and benefiting local communities*” [50]. This relationship will become the new model for stakeholders like NASA and NSF for all future partnerships.

6.2 Native Lands Usage

Moreover, this partnership has provided great insight into the use of Native lands for large U.S. projects and hopefully will change the way these projects are carried out with respect for and collaboration with the Native people. There are currently 10 telescopes in operation on Maunakea, with another location reserved for another facility, whether that be a telescope or an educational building. These telescopes make up the Maunakea Observatories and are operated by 12 nonprofit independent institutions (Appendix F). Caltech is decommissioning the Caltech Submillimeter Observatory (CSO), as mandated by sub-plan of the Maunakea Comprehension Management Plan [51]. The decommissioning plan was required as a condition of approval for the Management Plan in 2009 and it described a process for decommissioning observatories on Maunakea. This plan called for the dismantling of the CSO to being in 2016, returning the site to its natural state. Science operations ceased in 2015 for the CSO and as of September 2023, the telescope has been removed with deconstruction of the building the next step. It is expected that by spring or summer 2024, the site will begin land restoration, after a break for winter weather. The Canada-France-Hawaii Telescope (CFHT) is also planning for decommission, with the site being replaced by the Maunakea Spectroscopic Explorer (MSE), which plans to retain and reuse as much of the existing physical infrastructure as possible. There are also on-going plans to decommission the UH Hilo Hōkū Kea Telescope.

There are many examples of Native lands being used for large projects where the current situation is similar to the one we discuss here. Locations with analogous stories include Kitt Peak Arizona, Los Alamos New Mexico, and LIGO in Hanford Washington. The Kitt Peak

National Observatory (KPNO) was formally founded in 1958, after the lands were leased from The Tohono O'odham Nation. Although an agreement was made, new issues have been rising due to the new construction of buildings without new agreements in place. The Los Alamos National Laboratory (LANL) was founded in 1943 as a secret laboratory for the Manhattan Project as a research site and is now a federally funded research and development center solving national security challenges. The lands on which the laboratory was built, the Pajarito Plateau, was home to the Ancestral Pueblo people (a prehistoric Native American civilization that existed from approximately 100 to 1600 C.E), but the lands were abandoned in the 1500s due to drought and were unoccupied when LANL was founded. The Laser Interferometer Gravitational-Wave Observatory (LIGO) Hanford was founded in 1992, but the lands were originally used in 1943 for the Manhattan Project as a production site. The observatory sits on the ancestral lands of Indigenous peoples, including the Walla Walla, Umatilla, Yakama, Wanapum, Cayuse, Palouse, and Nez Perce peoples. These are just a few examples of how Native lands have been used previously and how different levels of conflict, cooperation and community engagement could contribute to long-term solutions and establish working and fruitful relationships.

In the past decade there have been efforts to increase the economic, cultural, and educational benefits of astronomy facilities for local and Native communities [50]. Examples of these efforts include the 'Imiloa Center in Hilo, Hawaii, and the program in place at the KPNO that coordinates with the Tohono O'odham Nation's tribal employment office. The LIGO Exploration Center (LExC) was opened in 2022 as an educational center with a goal of engaging underrepresented populations and creating a balance between culture and technology. The Astro2020 survey discussed ways to ensure alignment of current and future engagements with principals that the astronomy community can commit to in order to create the Community Astronomy model. These principals include: *Listen and empower*, *Aim to do good for all*, and *Invest in the future, together* [50].

After more than 50 years of building on Maunakea, the Native Hawaiian communities have continued to express strong feelings related to the past and future activities within the Maunakea Lands currently managed by UH. According to the opinions of some participants in the inception of Keck, the original approach of siting telescopes on Maunakea was seen as a continuing pattern of colonialism, with very little consideration to the ownership and ancestral value of the land and the native cultures. Furthermore, the majority of the promoters of establishing observatories were large institutions driven by project management practices, where the final product is all that mattered, rather than the process or the sensitivity of inclusion and outreach to the local communities. Also, Native cultures often have a different concept of the idea of land possession or ownership, which in most cases is translated into stewardship rather than into absolute proprietorship. With time these different perceptions and attitudes created a culture of resentment among the Native communities, which culminated with local protests during the start of the Thirty Meter Telescope construction phase in 2014. These protests may have had nothing to do with astronomy or its value and importance; rather, they had to do with cumulative grievances of past decades, even perhaps since Hawaii became a state in 1959 or even before, since Hawaii became a U.S. territory. These grievances include the lack of community and Native input to the process of operations and governance, lack of concern for protected species and the environment, ignoring the religious and spiritual significance of Maunakea and the indigenous Hawaiian culture.

6.3 Management of Complex Facility

In January 2022, the UH BOR adopted a new Master Plan for the UH Maunakea Lands and in creating the plan, the BOR received insights of Native Hawaiian cultural experts. This updated Master Plan gives special attention to the astronomy programs on which UH focused attention for three decades, but also to the place of honor and renown that Maunakea has in the history, culture, and hearts of the Hawaiian people. This Master Plan differs greatly from its predecessor and includes many commitments/strategies that broaden Native Hawaiian and community participation in planning and programming, and measures to reduce impacts to the cultural landscape and natural resources, especially in the summit region. Among these commitments includes: 1) by December 31, 2033, there will be not more than 9 operating astronomy facilities in the MKSR, 2) five of the 14 existing astronomy sites (as of 2020) will be ineligible for future astronomy use and can be repurposed for non-astronomy uses and education, 3) astronomy site 13 will be the last new site developed for an astronomy use in the MKSR, and 4) no land uses will be considered on major undeveloped cinder cones in the MKSR. Even with these commitments, concerns still remain regarding the Thirty Meter Telescope (TMT), the new land authorization beyond 2033, UH being the appropriate entity to manage the MKSR region, and that UH lands were stolen from the Hawaiian Kingdom.

Through the years, there have been many protests and lawsuits about the University of Hawaii's management of Maunakea. As it was suggested earlier, a possible explanation of these difficulties and conflicts is that since the inception of the observatories on Maunakea, the national and international institutions promoting the construction and operations of these facilities were organizations that valued formal system engineering practices with established key decision and gatekeeping points. This methodology focuses solely on the final product but not on the process itself, which is a valuable and important tool for community information, participation and subsequent engagement. Perhaps the absence of these parallel community activities and lack of public communication created an unintended distrust that was exacerbated with time. In 2019, more attention was brought to these issues over the attempted construction of the TMT (Appendix B.3) and because of this clash, the state decided to act and create a new agency to take over the management of Maunakea. The new Maunakea Stewardship and Oversight Authority (MKSOA) was established in Act 255, which was signed into law by Hawaii Governor David Ige in July 2022. After a 5-year transition period, the 11-member board will take over land disposition powers, including the granting of new leases for facilities on Maunakea after the current master lease expires in 2033 [52]. The new authority takes complete control on July 1, 2028, and until then will work jointly with the UH. The board is tasked with formulating a master plan to balance culture and environment with astronomy and economic benefits. This new stewardship was made *"in hopes of protecting the mountain for future generations while managing its lands and fostering collaboration so ecology, the environment, natural resources, cultural practices, education and science are balanced"* [52].

When discussing the new MKSOA with an appointed representative, Rich Matsuda, he said that in order to better connect the structure and governance issues with Native Hawaiians, "*we have to be part of the community shoulder-to-shoulder rather than face-to-face, showing that we are more cooperative and understanding rather than negotiative*" [53]. MKSOA is tasked with finding ways to move toward a community coming together and trusting in a model of mutual stewardship. The MKSOA is one concrete demonstration of a Community Astronomy Model as described in the Astro2020 report. This is not just an issue in Hawaii or with astronomy alone, but this model of mutual stewardship should be adopted across disciplines and become the new standard for the use of native, historical, and/or sacred lands for projects. Efforts from the MKSOA to adopt this model involved learning about the different interests for Maunakea and the appointed members realized that the one thing they all had in common was that they all deeply cared about Maunakea. By putting the care of Maunakea at the center, as the primary importance, and the individual interests (astronomy, recreation, culture, environment, and/or tourism) at the secondary level, a mutual stewardship could be formed.

Living within the community when trying to establish something in the area would be a significant positive factor for future projects, as it would result in stronger relationships and a greater mutual respect. This is the best way to develop understanding and build trust, which are keys for acceptance. When discussing this issue with Leslie Kissner, she told us *"I remembered some of the NASA representatives flying in for hearings with the Keck Observatory and wearing suits/ties, which is known to be common attire for the East Coast that demonstrates professionalism and respect. But it was mismatched to the 'local island style' and misread by some as arrogance"* [28]. This issue may have been resolved by having a liaison between the NASA and local communities to create bonds and a line of communication between the two parties, making this misunderstanding easily explainable. The future of similar partnerships can be based around the adopted values of Inclusion, Diversity, Equity, and Accessibility (IDEA), which are part of not only NASA's core values, but they are also being honored by W. M. Keck Observatory and by the other Observatory partners.

Maunakea Summit after development. (credit: W. M. Keck Observatory, 2023)

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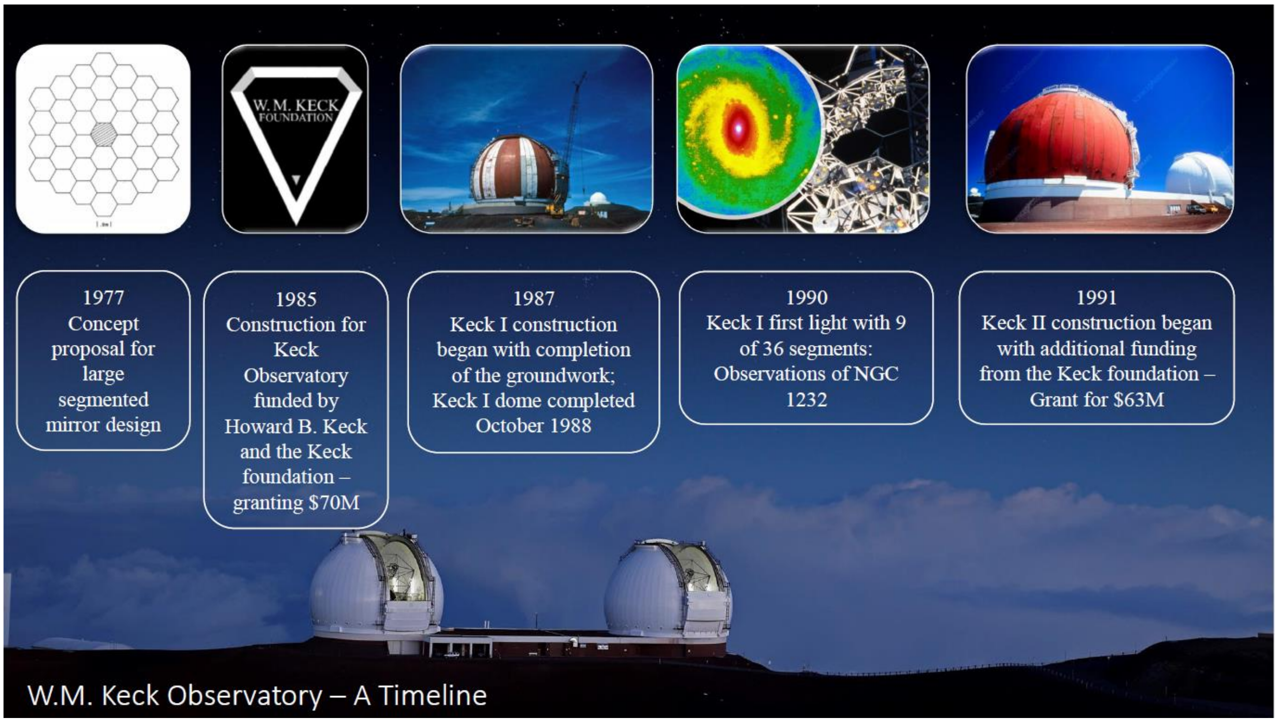
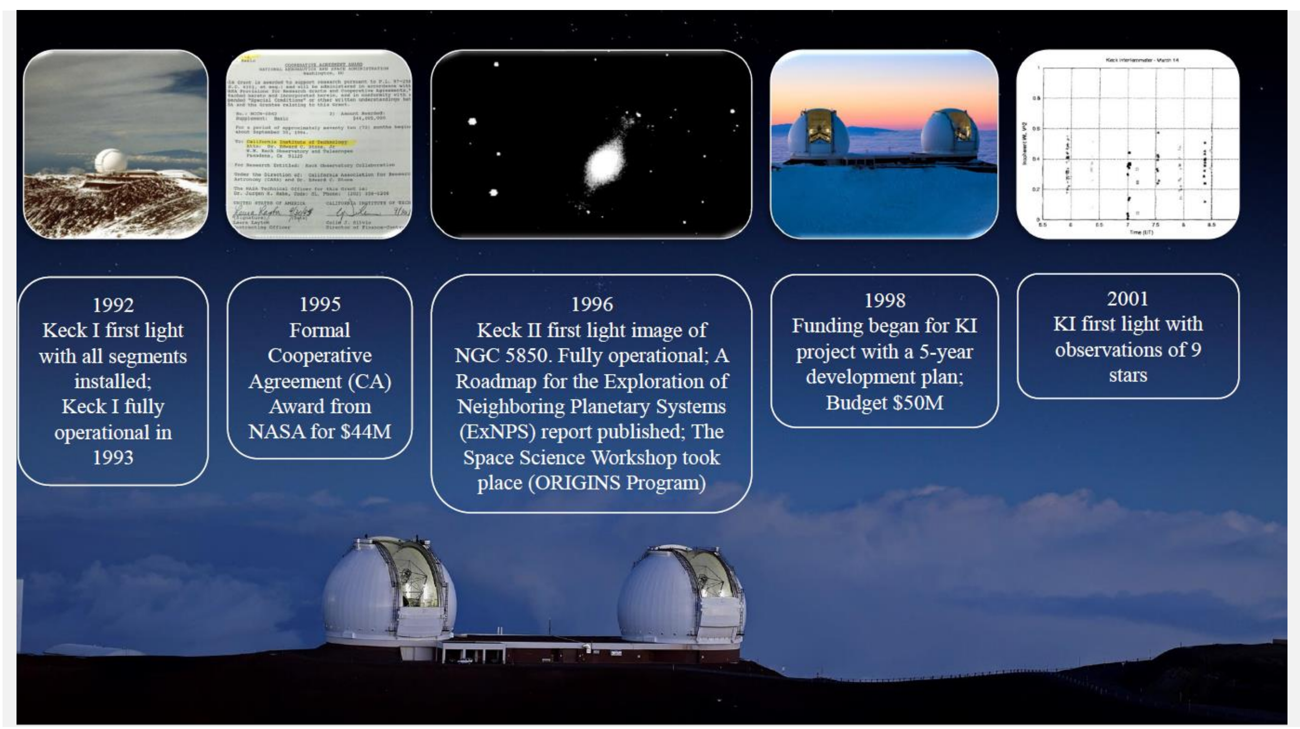
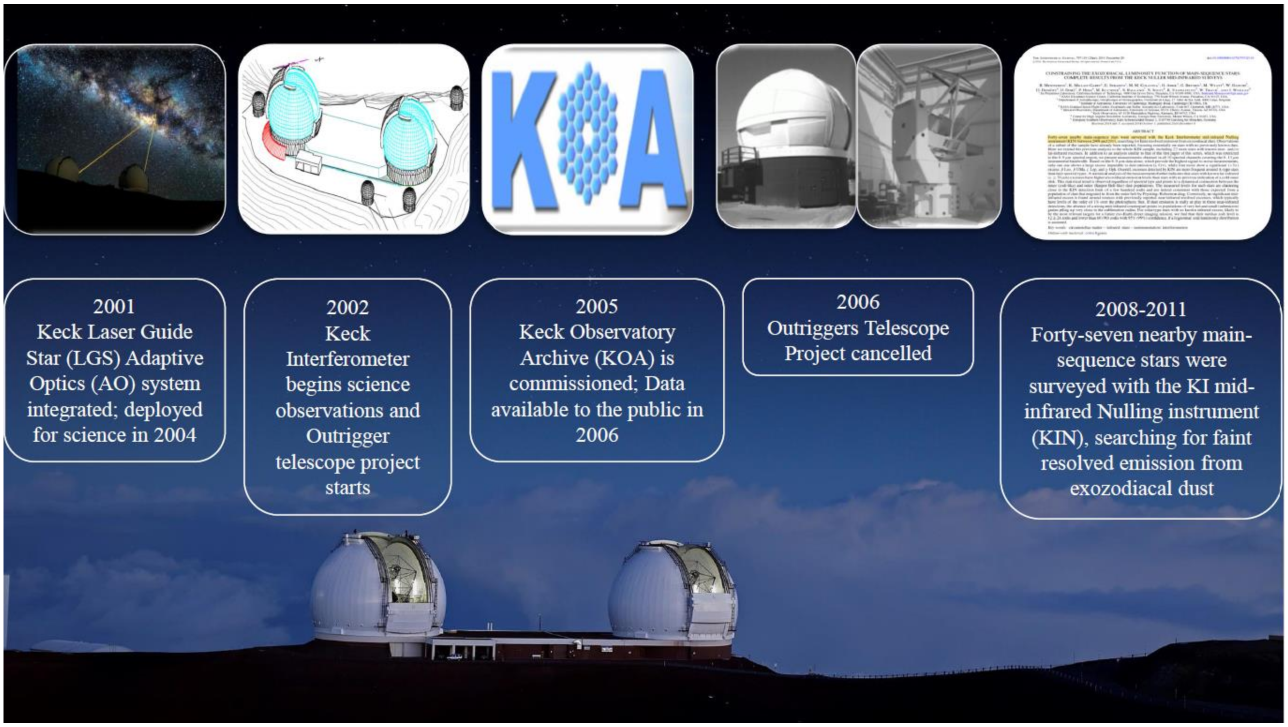
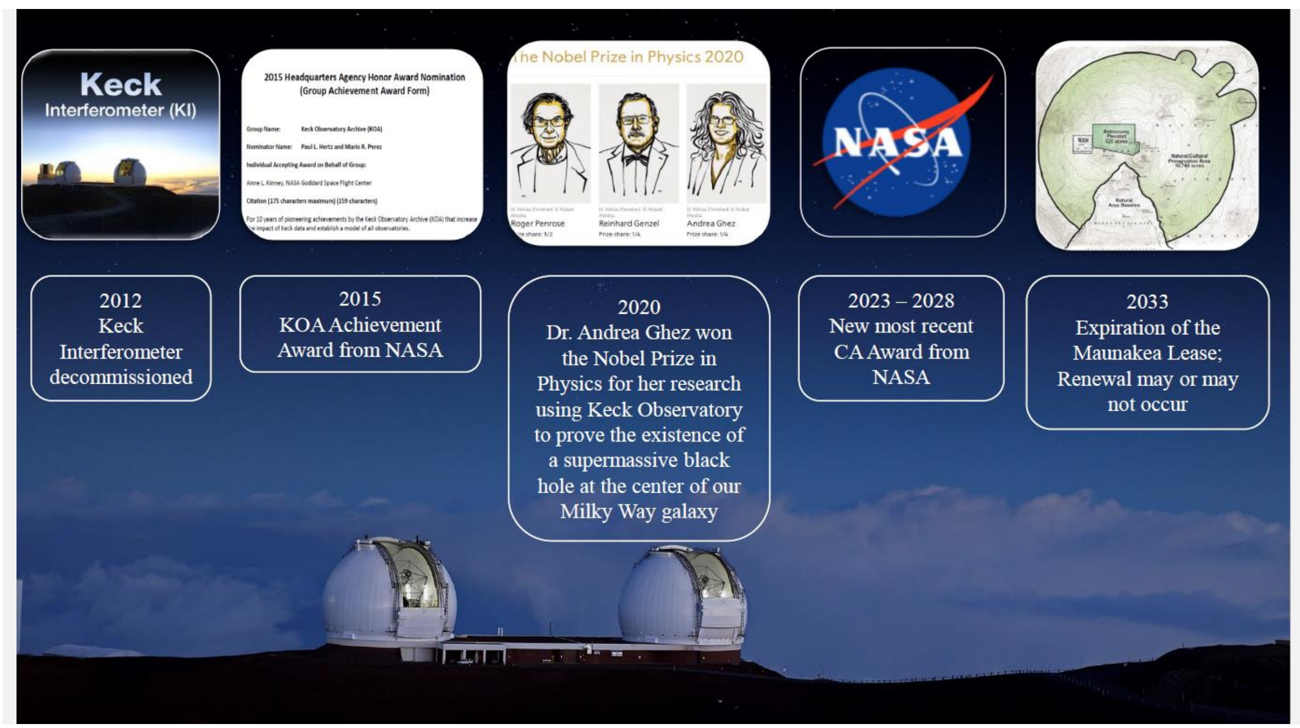
Appendix

A. Keck Chronology starting with the conceptual proposal in 1977 (credit: one of us (CNL)).






2001
Keck Laser Guide Star (LGS) Adaptive Optics (AO) system integrated; deployed for science in 2004
2002
Keck Interferometer begins science observations and Outrigger telescope project starts
2005
Keck Observatory Archive (KOA) is commissioned; Data available to the public in 2006
2006
Outriggers Telescope Project cancelled
2008-2011
Forty-seven nearby main-sequence stars were surveyed with the KI mid-infrared Nulling instrument (KIN), searching for faint resolved emission from exozodiacal dust


Keck
Interferometer (KI)
2015 Headquarters Agency Honor Award Nomination
(Group Achievement Award Form)
he Nobel Prize in Physics 2020
Roger Penrose
Reinhard Genzel
Andrea Ghez
NASA
2012
Keck Interferometer decommissioned
2015
KOA Achievement Award from NASA
2020
Dr. Andrea Ghez won the Nobel Prize in Physics for her research using Keck Observatory to prove the existence of a supermassive black hole at the center of our Milky Way galaxy
2023 – 2028
New most recent CA Award from NASA
2033
Expiration of the Maunakea Lease; Renewal may or may not occur

B. Legal Issues for NASA and the University of Hawaii

1. The legal issues between the Office of Hawaiian Affairs (OHA), the University of Hawaii Institute for Astronomy (UHIfA) and NASA have continued since the early stages of the Keck Observatory. The first lawsuit came in 2002 when OHA filed suit against Sean O'Keefe (NASA Administrator) and Rolf-Peter Kudritzki (UHIfA Director), alledging a violation of the National Environmental Policy Act of 1969 (NEPA), the National Historic Preservation Act (NHPA), and the Hawaii Environmental Policy Act (HEPA) in connection with the proposed construction of the Outrigger Telescopes. In the complaint, OHA asks the court to order that NASA prepare a full EIS for the Outrigger Telescope Project, as well as for all other federally funded projects affecting Maunakea. The complaint futher asks the court to declare that NASA and UHIfA violated NEPA, the NHPA, and HEPA, and to award litigation costs. The court determined that the previously released EA prepared by NASA indicating that the project would have "no significant impact" was inadequate, and directed NASA to prepare a new EA in accordance with the opinion that the EA does not consider the impact of development. NASA went ahead with a full EIS as a way to try and prevent further lawsuits.

2. The approval of the CDUP by the Board for the building of the outrigger telescopes came in October 2004, and this decision was not accepted by the Native Hawaiian and environmental groups. One month later a lawsuit was filed with the Hilo Circuit Count on behalf of the Sierra Club, Mauna Kea Anaina Hou, the Royal Order of Kamehameha I and a Native Hawaiian with genealogical ties to Mauna Kea. The lawsuit challenged the state's approval of a permit that would allow NASA to build the outrigger telescopes and called for an appeal of the permit. The groups argued that the project was not included in any state-approved management plan, and further that the addition of the outrigger project to the mountain would exceed the limit of 13 astronomy facilities set by UH's 1985 management plan.

3. Issues continued with the Thirty Meter Telescope (TMT) project. Ground broke for the TMT in 2014 but was followed by a powerful protest. The construction permit to build was rescinded by the Hawaii Supreme Court at the end of 2015, following many protests and hearings from those who opposed the building of any more telescopes on Maunakea. The next couple years consisted of continued hearings until ultimately in 2017 the building permit was granted, but with a number of conditions. This approval was immediately appealed with the Hawaii Supreme Court but ruled in favor of TMT. Following the restart of construction in June 2019, protests started again. Construction has been at a stand-still, but with the new MKSAO established, the future of Maunakea and astronomy will be shaped by the board's decisions.

C. Funding Chart

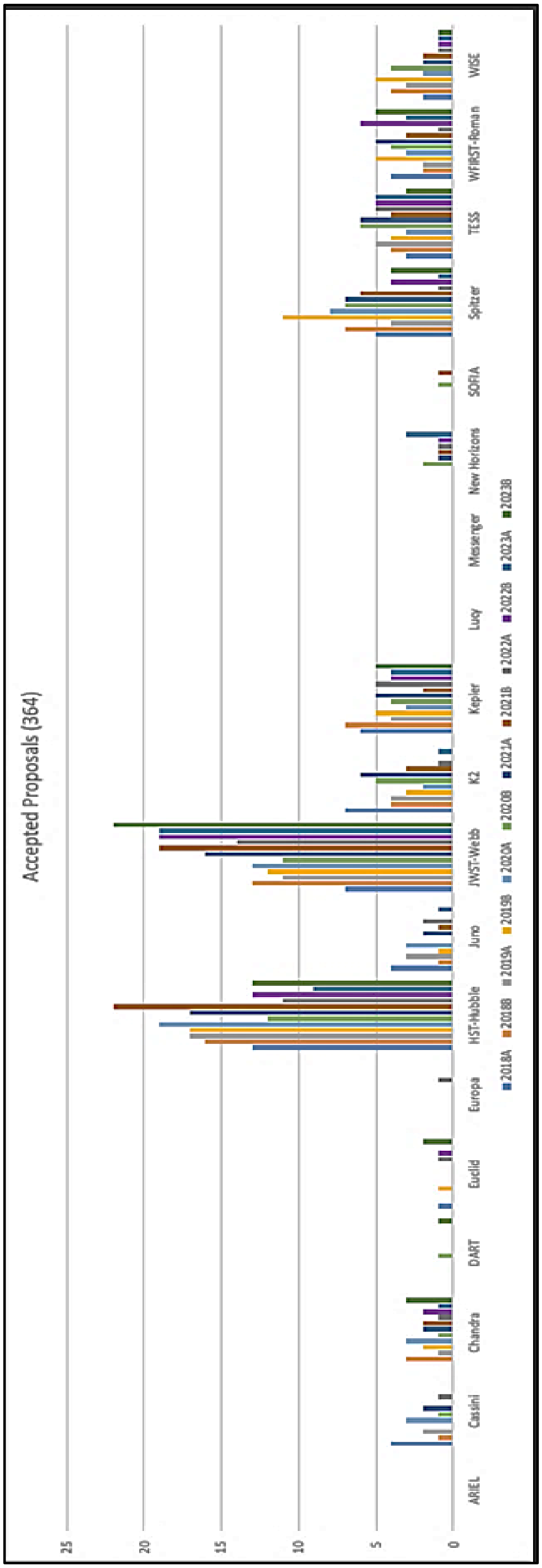
W.M. Keck Observatory Funding from NASA																
		3-year NASA Agreement with 3-year renewal option						*3-year NASA Agreement*			*2.4-year Agreement**		*5-year NASA Cooperative Agreements (began 3/1/08)*			
Year	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008 - 2013**	**2013 - 2018**	**2018 - 2023**	**2023 - 2028**
Total	**209,000**	**1,826,000**	**2,300,000**	**2,772,000**	**2,266,000**	**3,014,000**	**2,453,000**	**2,863,000**	**2,827,000**	**43,822,000**	**7,173,000**	**8,312,000**	**30,535,000**	**19,277,000**	**22,790,650**	**24,798,000**
Grand Total	**177,237,650**															
											*NASA ended this agreement earlier to begin the new 5-year agreement			* These totals can be divided by 5 to get the total per year during the CA period		

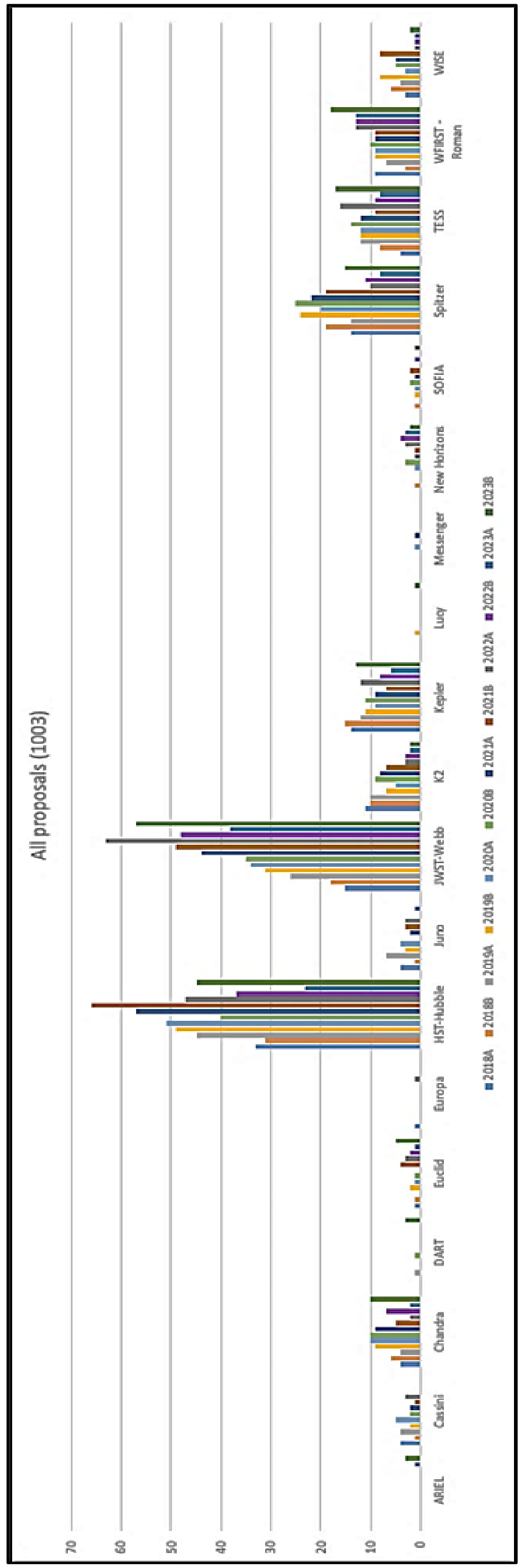
D. Guido Horn d'Arturo and the First Segmented Mirror

Guido with the completed 1.8-m segmented telescope with 61 segments in 1952 (credit: **[13]***)*

The 1.8-m segmented telescope located in its original seat inside the Museo della Specola in the ancient tower. (credit: **[13]***)*

E. Space Mission Support





F. Telescopes on Maunakea and Current Status

Logo	Name	Status
	UH88	Active Operated by the University of Hawaii
	Very Long Baseline Array	Active Operated by the National Radio Astronomy Observatory
	Caltech Submillimeter Observatory	Suspended operations in 2015 Decommissioning ongoing
	Canada-France-Hawaii Telescope	Active Plans for replacement by the Maunakea Spectroscopic Explorer ongoing
	Gemini Observatory	Active Operated by NSF's NOIRLab
	NASA Infrared Telescope Facility	Active Operated by the University of Hawaii
	James Clerk Maxwell Telescope	Active Operated by East Asian Observatory

	Subaru Telescope	Active Operated by the National Astronomical Observatory of Japan
	Submillimeter Array	Active Operated by the Smithsonian Astrophysical Observatory and the Academia Sinica Institute for Astronomy and Astrophysics
	United Kingdom Infrared Telescope	Active Operated by the University of Hawaii
	W. M. Keck Observatory	Active Operated by CARA
	UH Hilo Hoku Ke’a Telescope	Decommission ongoing

GLOSSARY

Abbreviation	Definition
AGN	Active Galactic Nuclei
AO	Adaptive Optics
APD	Astrophysics Division
BLNR	Board of Land and Natural Resources
BOR	Board of Regents
CA	Cooperative Agreement
Caltech	California Institute of Technology
CARA	California Association for Research in Astronomy
CDP	Complex Development Plan
CDUP	Conservation District Use Permit
CEERS	Cosmic Evolution Early Release Science Survey
CMP	Construction Management Plan
COMPLEX	Committee on Planetary and Lunar Exploration
COR	Cosmic Origins
DEA	Draft Environmental Assessment
DLNR	Department of Land and Natural Resources
DSI	Data Services Initiative
EA	Environmental Assessment
EIS	Environmental Impact Statement
EOS	Electro Optics Systems Pty Limited
EOST	Electro Optics Systems Technologies
ESO	European Space Observatory
ExEP	Exoplanet Exploration
FEA	Final Environmental Assessment
FY	Fiscal Year
HEPA	Hawaii Environmental Policy ACT
HIRES	High-Resolution Echelle Spectrograph
HPD	Heliophysics Division
HST	Hubble Space Telescope
HQ	Headquarters
IDEA	Inclusion, Diversity, Equity, Accessibility
IRTF	Infrared Telescope Facility
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KI	Keck Interferometer
KOA	Keck Observatory Archive
KPNO	Kitt Peak National Observatory
KSMS	Key Strategic Mission Support
LANL	Los Alamos National Laboratory
LGS	Laser Guide Star
LIGO	Laser Interferometer Gravitational-Wave Observatory
MKSOA	Maunakea Stewardship and Oversight Authority

MKSR	Mauna Kea Science Reserve
NASA	National Aeronautics and Space Administration
NAOJ	National Astronomical Observatory of Japan
NEPA	National Environmental Policy Act
NExScI	NASA Exoplanet Science Institute
NGC	New General Catalogue
NGS	Natural Guide Star
NHPA	National Historic Preservation Act
NIRCam	Near-Infrared Camera
NIRC2	Near-Infrared Camera 2
NN-Explore	NASA-NSF Exoplanet Observational Research Program
NOA	Notice of Availability
NPOI	Navy Precision Optical Interferometer
NSF	National Science Foundation
NSSDCA	NASA Space Science Data Coordinated Archive
OEQC	Office of Environmental Quality Control
OHA	Office of Hawaiian Affairs
ORCAS	Orbiting Configurable Artificial Star
ORKID	ORCAS Keck Instrument Demonstrator
OTP	Outrigger Telescope Project
PAST	Planetary Astronomy Program
PCOS	Physics of the Cosmos
PS	Planetary Science
PSD	Planetary Science Division
RDP	Research Development Plan
RST	Roman Space Telescope
SMD	Science Mission Directorate
SSO	Solar System Observations Program
SWG	Science Working Group
TESS	Transiting Exoplanet Survey Satellite
TMT	Thirty Meter Telescope
TOPS	Toward Other Planetary Systems
UC	University of California
UH	University of Hawaii
UHIfA	University of Hawaii Institute for Astronomy
USNO	U.S. Naval Observatory
WMKO	W. M. Keck Observatory

[*] The University of Hawaiʻi at Hilo College of Hawaiian Language, Ka Haka ʻUla o Keʻelikōlani, recommends one word, "Maunakea" as the proper Hawaiian usage. Ka Wai Ola (Vol. 25 No. 11) also identifies "Maunakea" as the traditional Hawaiian spelling. The "Mauna Kea" spelling is only used in this document where "Mauna Kea" is used in published or legal documents.

[†] The individuals who died due to the fire at the Subaru Telescope in 1996: Marvin Arruda 52, Ricky Del Rosario 38, and Warren K. "Kip" Kaleo 36.