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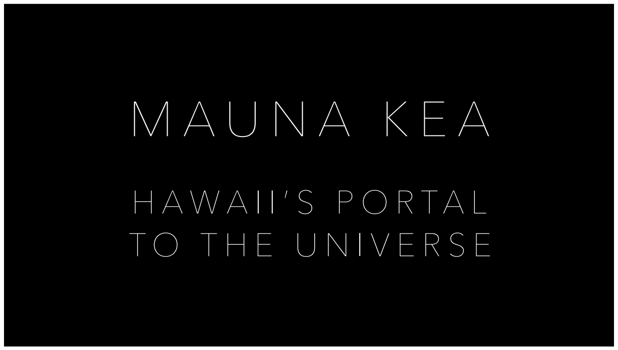

- Aloha! Tonight I'd like to share the story of a remarkable place — Mauna Kea, on the Big Island of Hawaii, a place I called home for 16 years before moving here to Colorado.
- I'll explain what makes the Big Island a great place for astronomy, describe the abundance of excellent observatories that dot the summit of Mauna Kea, discuss what goes into collecting astronomical observations, relate the cutting-edge technology that's changing how we observe, and speculate on what the future holds for Hawaii.

2

- Earlier this year, people around the world watched in amazement as lava from the Kilauea volcano covered parts of the Big Island.

3

- This not a new process, but one that has taken place for millions of years.
- Eruptions gave birth to all of the Hawaiian islands as the earth's pacific plate glides across the hotspot underneath the seabed and brings a chain of volcanic islands into being.

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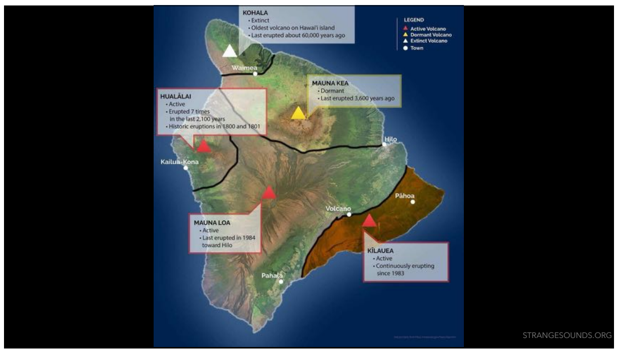
- The story of Mauna Kea begins nearly a million years ago, when an undersea volcano already 20,000 ft high first emerged from the ocean and continued building until it stood miles above the ocean.



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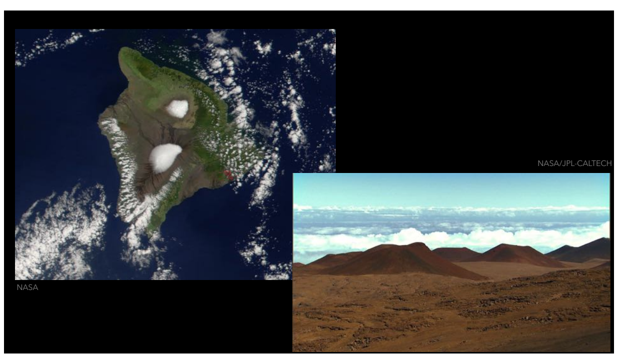
- As the Pacific plate continued its slow drift, the hotspot moved on to form other volcanoes -- Hualalai, Mauna Loa, and Kilauea -- to merge with Mauna Kea and Kohala and form the largest island in the Hawaiian chain.



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- Periodic ice ages brought glaciers which carved up the mountain's summit.
- About 13000 years ago, the last ice age ended and the final glaciers melted.
- Just 4000 years ago, the last eruptions built the most recent cinder cones on the top and flank of the mountain.
- The mountain sleeps now, but it will someday erupt again.

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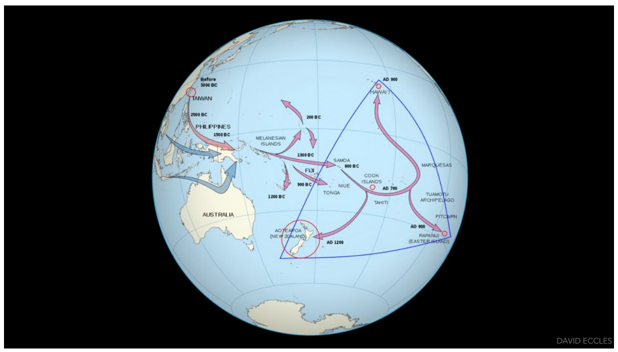
- Meanwhile, human civilizations began to venture out across the pacific ocean in their new invention, the outrigger canoe.



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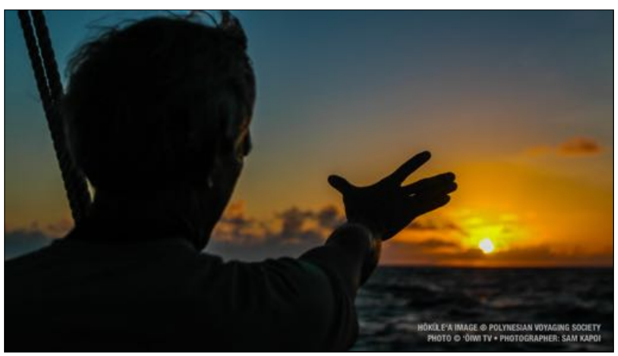
- These adventurous people hopped from island to island across polynesia, and then made the long voyage from Tahiti north to discover the world's most isolated landmass over 1000 years ago.



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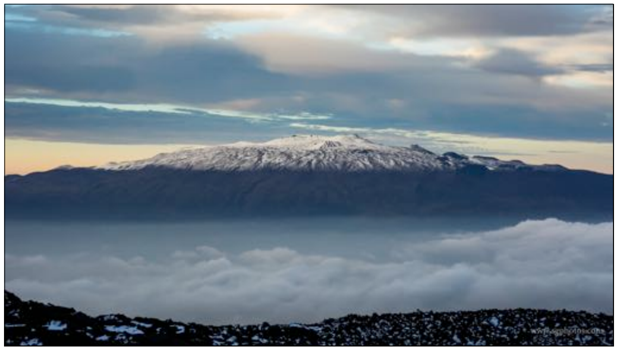
- The polynesian voyagers were expert celestial navigators, and used the stars to guide their path through the vast ocean.
- And so from the very beginning, Hawaii and astronomy were connected.



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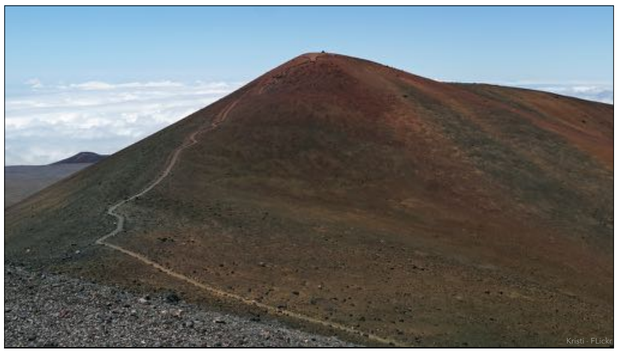
- The settlers of Hawaii made the islands their new home and eventually built a society that was among the most advanced in the pacific and which thrived for centuries.
- These people revered the summit of the tall mountain that could be covered in snow any season of the year.
- They named it Mauna Kea, the white mountain.



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- The mountain was a holy place to them, one that only certain exalted people were allowed to climb.
- With no horses to carry them, the arduous hike up the mountain must have taken days.
- At the inhospitable summit, the thin air and cold temperatures make it painful to remain more than a few hours.

12

- Aside from its religious role, Mauna Kea was also an important resource for the Hawaiian society as the source of the very best rock that could be turned into hard tools.
- With no access to metal in this young landscape, people across the pacific coveted the knives and axes made from these precious stones to use in carving canoes and carrying out their lives.

13

- From the summit of Maunakea you can gaze down on 4 of the 5 major climate zones on earth: the tropical beaches on the coast, the rain forest of the windward hills, the arid desert of the saddle, and the tundra of the summit
- The only major zone not represented is the cold continental climate that we enjoy here in Colorado, which is why you won't find apple and peach trees in Hawaii.

DIEGO DELSO, DELSO.PHOTO / ERIC TESSMER - FLICKR / ERIK WILDE - FLICKR / WASIF MALIK

14

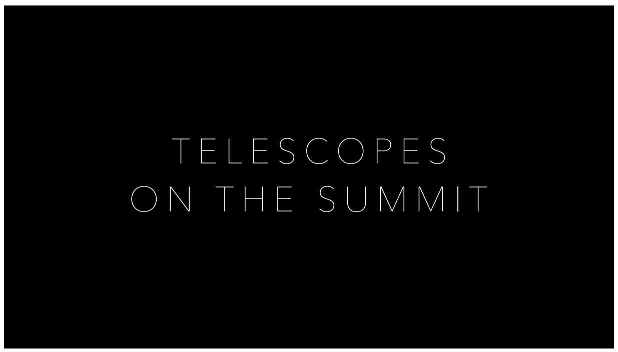
- The arrival of Captain Cook's fleet in 1778 brought contact with European peoples.
- With this exposure came new diseases that decimated most of the the native population.
- But the contact also brought opportunities, and the monarchs of hawaii sought to advance their society by adopting new ideas from the western world.

15

- The last king of Hawaii, David Kalākaua, sought to modernize his society and traveled the world to learn the ways of others.
- In 1881 he came to california and visited the fledgling Lick Observatory under construction.

16

- At the time, this observatory was building its first telescope, a 12" refractor by famed lens maker Alvan Clark which was among the larger in the world at a time.
- Richard Floyd of Lick Observatory had met the King several years earlier on a trip to Hawaii.
- When the King wanted to visit Mt. Hamilton, Floyd set up the telescope temporarily in the unfinished dome, and the privilege of making the first observations with this telescope fell to King Kalakaua.
- This was the second connection between Hawaii and astronomy.



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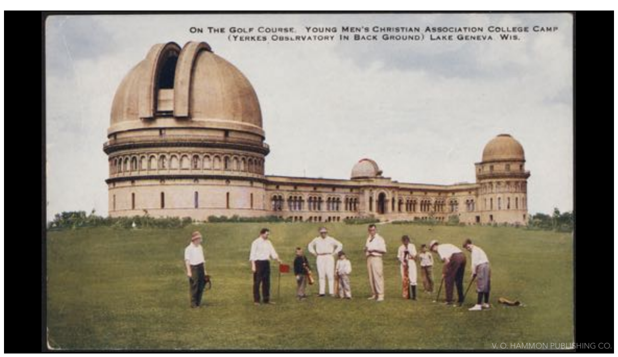

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- Astronomy enters the story of Mauna Kea rather recently, in the late 20th century.
- For centuries, astronomers built telescopes at colleges in cities.
- Then astronomers began to understand the merits of building telescopes in places outside of cities - in places like Lake Geneva Wisconsin, where the University of Chicago built the Yerkes Observatory, home to the 40-inch refractor that was the world's largest in 1897.

19

- Out west, astronomers realized that putting telescopes at higher elevations could improve the view of the stars.
- That led James Lick to fund the construction of the observatory bearing his name in 1888 atop Mt Hamilton outside of San Jose.

20

- In the middle of the 20th century, the dutch-american astronomer Gerard Kuiper founded the famed Lunar and Planetary Laboratory at the University of Arizona.
- He began a quest to locate not just a good site for an observatory, but the spot with skies so clear and images so sharp that it would qualify as the best on the planet to place a telescope.

21

- In 1963 Kuiper journeyed to Hawaii to check out the condition atop Haleakala the extinct volcano on Maui whose name literally translates as “house of the sun.”
- Fittingly, the University of Hawaii had built a solar telescope to study the sun, a trend which continues to this day with the construction of the new Daniel K. Inouye Solar Telescope slated to begin operations next year.

22

- Kuiper's nighttime observations made from Haleakala confirmed the quality of the seeing -- when the skies were clear.
- Unfortunately, that was relatively rare, as nighttime clouds frequently blanketed the summit.
- Instead, he turned his attention to the neighboring island of Hawaii, known as the Big Island.

23

- Both major volcanos on the Big Island, Maunakea and Maunaloa, tower more than a mile higher than Haleakala and held promise that they might remain above the clouds.
- Maunaloa had the key drawback that it was still a very active volcano, erupting on average every 6 years.
- Instead, Kuiper turned his attention to neighboring Maunakea and found that indeed, the conditions at its summit exceeded even his high expectations.

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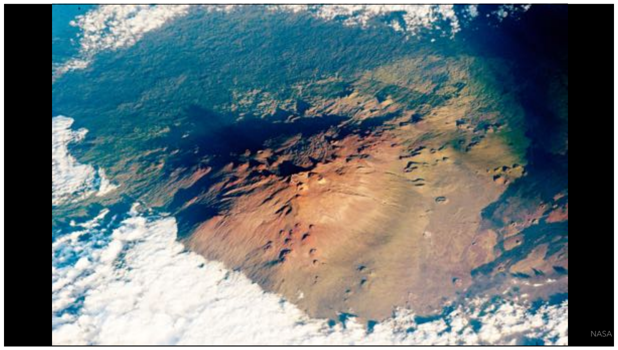
- He exulted: This mountaintop is probably the best site in the world -- I repeat, in the world -- from which to study the moon, the planets, and the stars..it is a jewel!" Fifty years later, evidence has borne out his finding.



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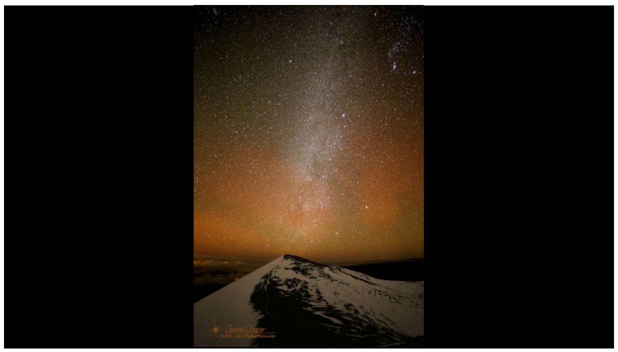
- What are the reasons that this particular spot produces such fabulous observing conditions?
- First of course is the height of the summit. At 13,800 feet, the peak is not as high as some of Colorado's highest peaks, but it towers above all but one other peak in the pacific islands. This puts the peak well above the clouds on most nights and ensures a clear view of the sky.



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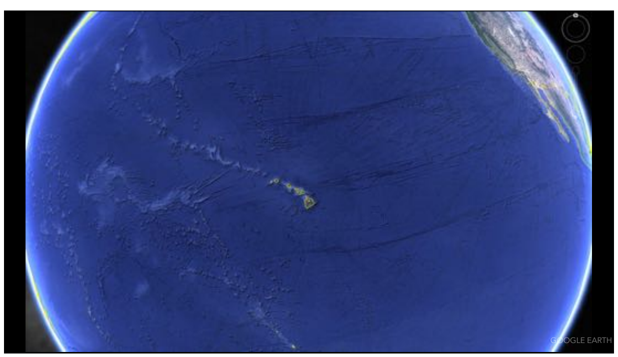
- Also important is the thinness of the air. On clear nights, air is the astronomer's enemy, putting a twinkle into the images of stars that makes them dance and blur. With the summit standing above ⅔ of the atmosphere, there is simply less air to disturb the images.



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- Third is the isolation of the peak. Unlike the mountains in colorado, the air above mauna kea has traveled uninterrupted for a thousand miles before encountering the peak of mauna kea. This smooth flow of air -- what astronomers call a "laminar flow" -- produces even less of the blur than normal air.

28

- A fourth factor is the dryness of the air. We think of Hawaii as warm and humid, but the cold thin air above Maunakea has 97% less water vapor than normal air, and this water vapor is the enemy of infrared astronomy because water molecules are excellent absorbers of infrared light. The thin, dry air atop Maunkea allows us a far clearer view of the infrared sky.

29

- Also, the skies in Hawaii are wonderfully dark. The big island has 10 times as much land as the neioghboring island of Oahu and only 1/10th the population -- there are no big cities other than Hilo, which is only half the size of Longmont. Plus, the island has strict laws to ensure that outdoor lighting -- from government, business, and homes, is properly shielded and astronomy friendly. This preserves the precious darkness of the night skies for the telescopes and those lucky enough to venture outside on a dark night and behold the Milkyway overhead.

30

- Crucially, Mauna Kea was accessible. There was no road to begin with, but the gradual slope of the mountain meant that within the span of a few weeks, a road was built allowing vehicles to drive all the way to the summit. This sets Mauna Kea apart from other mountains such as Puncakjaya.jpg in Indonesia, which is thousands of feet higher but not a mountain you can drive up.

31

- Kuiper had found his holy grail, an observing site above all others, but after all his efforts he failed to win the contest for funding to build a telescope there.

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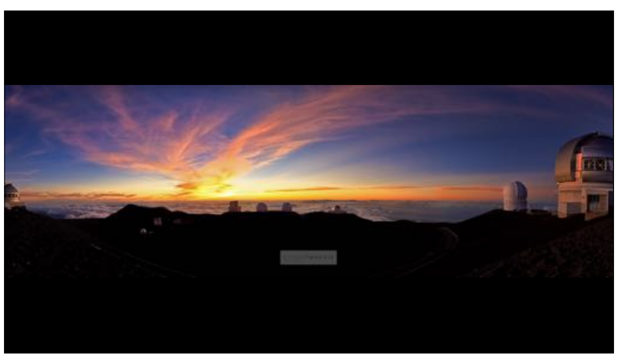
- That honor went to the University of Hawaii, which built a small demonstration telescope in 1968 and then the first large telescope on Mauna Kea in 1970: a 2.2-meter telescope that clearly demonstrated the amazing quality of the data one could obtain at the summit.



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- This success attracted international attention, and before the end of the decade international partners embarked on a telescope building campaign that established Maunakea as the planet’s most important astronomical mountaintop.

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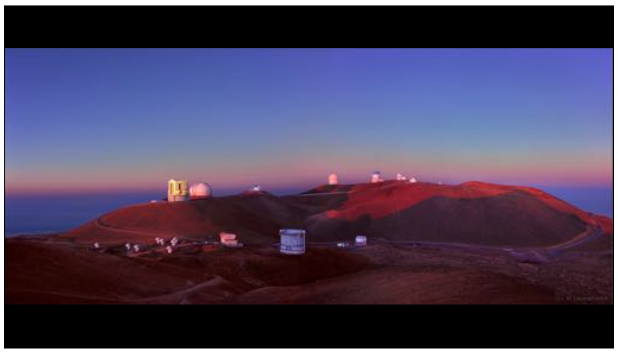


35

- Today, the array of observatories atop Mauna Kea provide an unsurpassed primer on the variety of telescopes and the amazing evolution in telescope designs over the last 50 years.

36

- CFHT
- The first of the larger observatories was the Canada-France-Hawaii telescope, an optical telescope with a 3.6-meter mirror that saw first light in 1979.
- At that time, it ranked as the 6th largest telescope in the world.

37

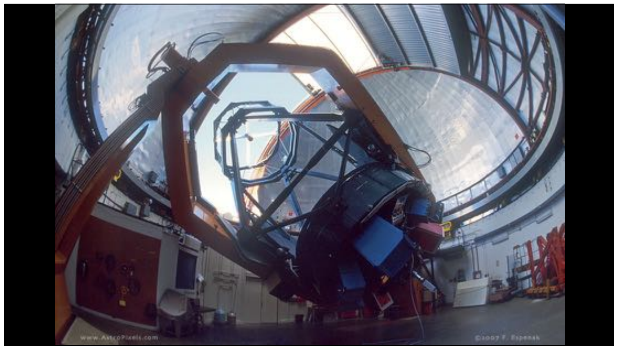
- As the first of the large domes, it sits at the best and most prominent spot on the summit.
- It has a sizable dome to accommodate the telescope's massive equatorial mount.

38

- IRTF
- Two other telescopes appeared that same year: NASA built the IRTF, a 3-meter telescope optimized for infrared observations to support space missions.

39

- This telescope was designed to allow quick changes of instrument, allowing the observers to change their camera to a different one within 15 min.
- Because these infrared sky is only a little brighter in the day than at night, this telescope can actually be used in the daytime to observer comets and other bodies in the solar system.



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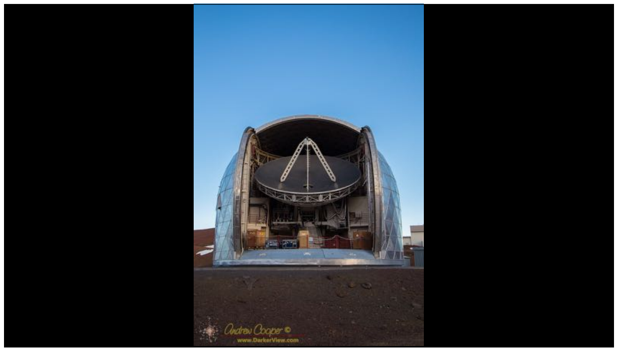
- The other telescope that came online that year is the UKIRT, a 3.8-meter telescope built by the British government which remains the largest telescope in the world designed for infrared observations.
- This was one of the first telescopes to use a primary mirror that was simplified and reduced in mass by using a thinner design that saves ⅔ of the mass.
- Despite its continued productivity, the UK has recently transferred control of this telescope to a consortium of the University of Hawaii and University of Arizona and Lockheed-Martin, which use some of the observing time to search for orbital debris around the earth.



41

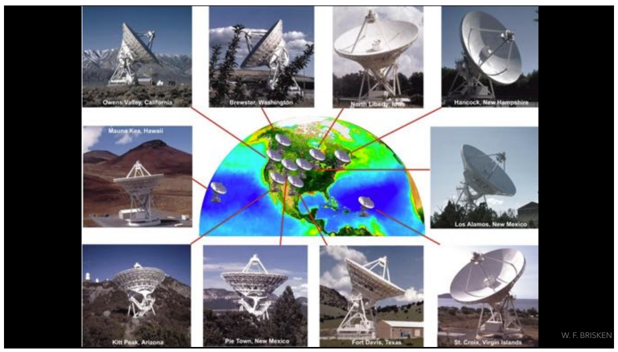
- CSO
- Mauna kea is not only a great place for optical and IR astronomy, but also for observing at longer wavelengths due to the lack of humid air that blocks radio waves.
- In 1986, Caltech built the first radio telescope on Mauna Kea.
- The Caltech Submillimeter observatory or CSO has a 10-meter dish covered with aluminum panels that focus radio light onto a detector.

42

- It was used for studies of cold gas and molecular clouds that are distributed throughout the Milky Way.
- The telescope features a distinctive dome that led to its nickname as “Marvin the Martian”.
- It was the only telescope on the mountain which is entirely operated by the astronomer with no observing assistant present to drive it.
- Caltech closed this telescope in 2015 and will return the site to its natural state.

43

- VLBA
- The largest dish on the summit is the VLBA telescope, a 25-meter dish built in 1992 that’s just one part of a giant radio telescope called the Very Large Baseline Array.
- The entire observatory includes 10 identical telescopes distributed from Hawaii to the US Virgin Islands in the Caribbean.



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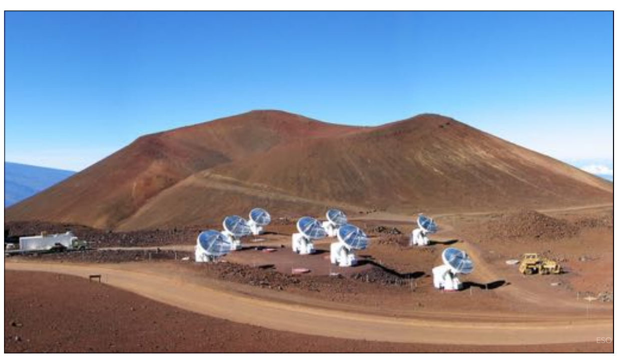
- Controlled from VLBA headquarters in New MExico, the signals collected by these 10 telescopes can be combined to act like one giant radio telescope that’s 5,000 miles across. This allows the telescope to resolve details in distant objects more precisely than any telescope on earth.



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- SMA
- The newest telescope at the summit is another radio telescope, the Submillimeter array or SMA, which is owned by the Smithsonian Institution and the government of Taiwan and began operations in 2004.

46

- This telescope includes 8 separate dishes, each 6 meters across, and the dishes can be moved to up to 24 different locations to act like a giant “zoom lens”. When close together, the telescope acts like a wide angle lens on a camera, viewing a larger area with less details.

47

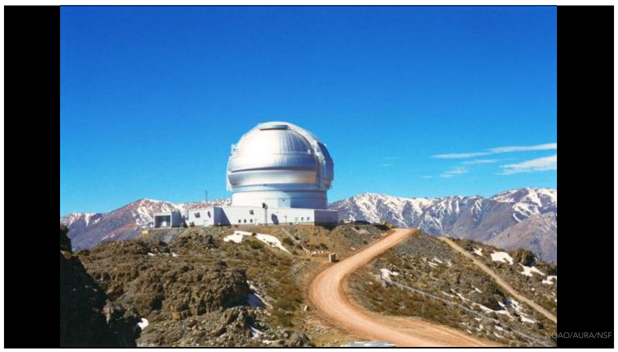
- When placed far apart, the zoom lens is a telephoto camera that provides great detail on a smaller area of the sky.

48

- The SMA, like other radio telescopes, is well suited for studying the cold clouds of gas that act as stellar nurseries and form new stars.

49

- After more than a decade without a new optical telescope atop Maunakea, 4 arrived in rapid succession in the final years of the century.
- These were the first of a new generation of telescopes that dwarfed the previous era’s best, a leap that was made possible by advanced in telescope technology.
- The Gemini-North telescope, with an 8-meter primary mirror, came online in 1999.



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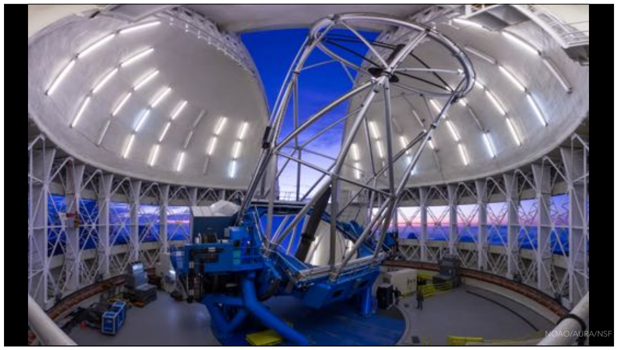
- The telescope is named after the constellation of Gemini, the twins, and the Gemini telescope has a twin located in Chile that came online in 2001, allowing the Gemini observatory to view of both the southern and northern skies.
- These telescopes are so expensive that it made sense for the US National Science FOundation to seek international partners to build the telescopes. In this case, the current partner nations include the US, Canada, Chile, Argentina, Brazil, Australia and South Korea.

51

- Two key technology breakthroughs allow these new telescopes to be built.
- In the old days, you created the main mirror by starting with a flat blank a glass and grinding out the material in the middle to make the parabolic shape required to focus the light. This painstaking process took years and could only produce mirrors up to 5 meters in size.
- New mirror making techniques allow allows the creation of “meniscus” style mirrors which are formed in the right shape and can be polished in only a year or so. These thin mirrors would deform as they moved to track the sky, so computer controlled support systems constantly compensate for the effect of gravity to maintain the precise shape of the primary mirror.



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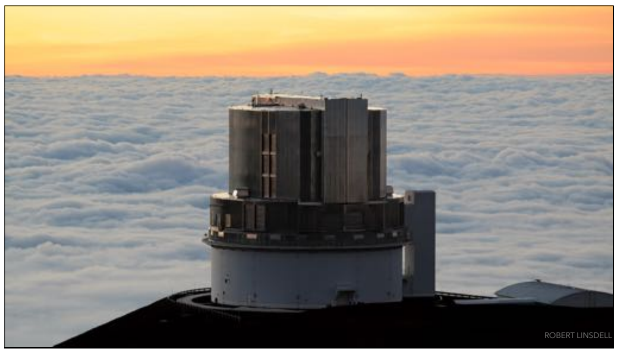
- Computers also allow the mount of the telescope to be simplified. Instead of the massive equatorial mounts of the telescope made before computer controlled telescopes, the new telescopes use the far simpler alt-azimuth mounts.
- The Gemini telescopes have made substantial contributions in studies of exoplanets.



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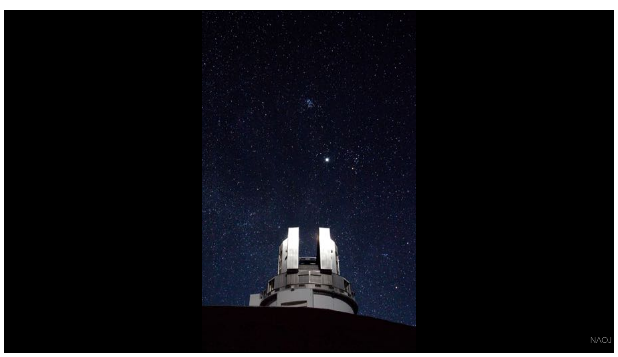
- Lured by the outstanding observing conditions atop Maunakea, the government of Japan decided to place its leading telescope in Hawaii rather than in Asia.
- Like Gemini-North, the Japanese Subaru telescope saw first light in 1999 and has an 8-meter meniscus primary mirror made of a single piece of glass.



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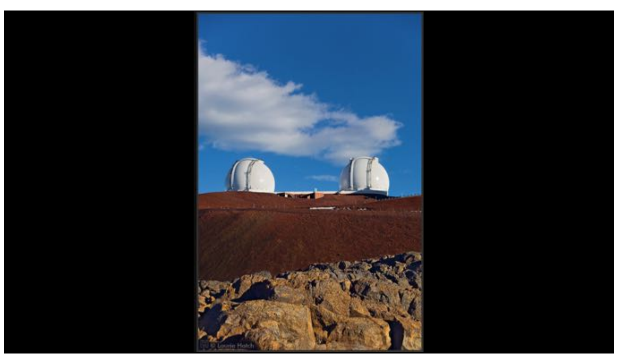
- The telescope is named for the familiar star cluster we call the Pleaides or “seven sisters” that graces our winter skies, which the Japanese call Subaru.
- The telescope features an unusual dome that allows air to pass smoothly past the telescope with minimal turbulence to maintains the exceptional seeing at the summit.
- As a result, the Subaru telescope excels at taking sharp images over wide areas of the sky.

55

- Two other telescopes occupy the final place on the summit, the twin telescopes of the Keck observatory, jointly built by the University of California and Caltech.
- The Keck I telescope saw first light in 1993, becoming the largest on the planet, dethroning Caltech's famous 200-inch telescope on Palomar mountain.

56

- Keck II followed in 1996.
- They're the king and queen of the summit, with primary mirrors 10 meters in diameter. Just for fun, let's illustrate how big that is!



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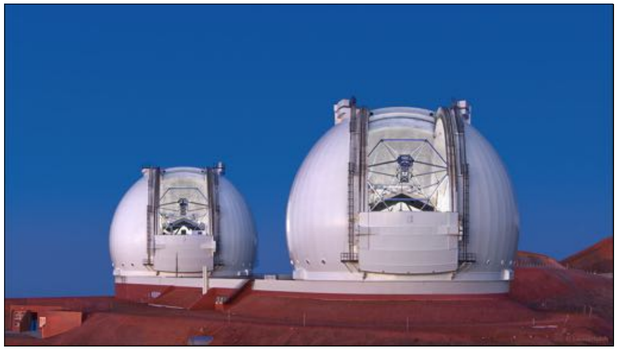
- Rather than being funded by a national government, the Keck telescopes were built by two universities through a generous gift from the foundation launched by a generous benefactor, the oil baron William Keck.



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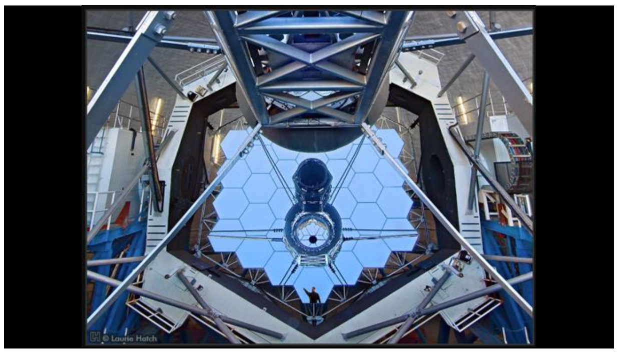
- These telescopes had an immediate impact like no other ground-based telescopes in our lifetime. The light gathering power of these behemoths made it possible to do in just one night projects that previously would take weeks to complete, and the lucky astronomers who had access to these private telescopes had a huge leg up on their competitors.



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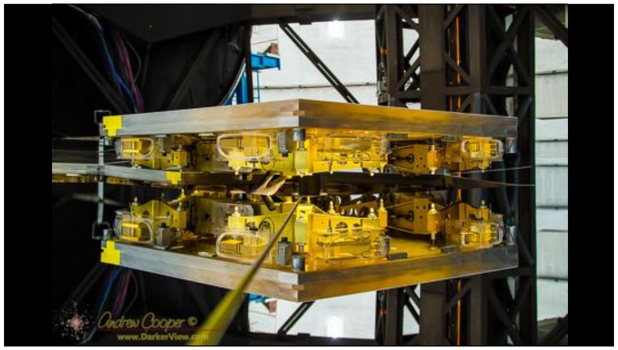
- The Keck telescopes represent another major advance in telescope design: instead of being made of a single piece of glass, the primary mirror on these telescopes consists of many smaller mirrors arranged in a honeycomb shape that act as one huge mirror.
- They are quite an engineering marvel!

60

- First, the creators of the telescope worked with optical labs to invent new techniques to grind and polish the mirrors to the correct shape in record time. The key problem is that each segment represents one piece of a parabola, but the parabolic center is way off axis. The engineers learned that they could take a round mirror blank and put it in a vise to deform the surface, grind a spherical shape into the surface, slice off the ears to form a hexagon, and then the segment would relax into the exact right shape.



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- Once installed in the telescope, the alignment of the mirrors must be precisely aligned with its neighbors to a few nanometers -- 1/25,000 the width of a human hair -- to act like a single mirror. A dedicated computer system adjusts the mirror position twice each second to correct the position of each segment.

62

- Thanks to the huge primary mirrors and the terrific cameras attached to these telescopes, the Keck Observatory has been a phenomenal success. The brilliant segmented mirror design can be scaled up to even larger telescopes, as we will see later. Although now surpassed by slightly larger telescopes in Spain and Chile, the Keck twins remain the most scientifically productive telescopes on earth.

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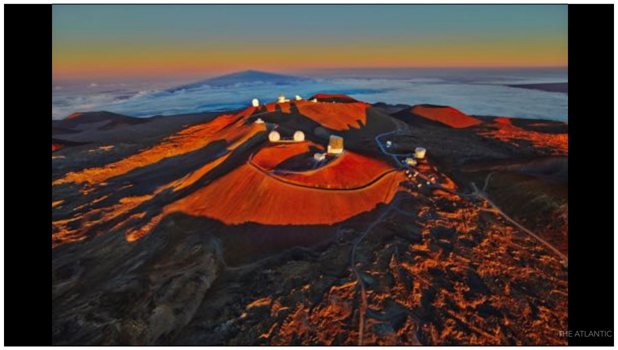
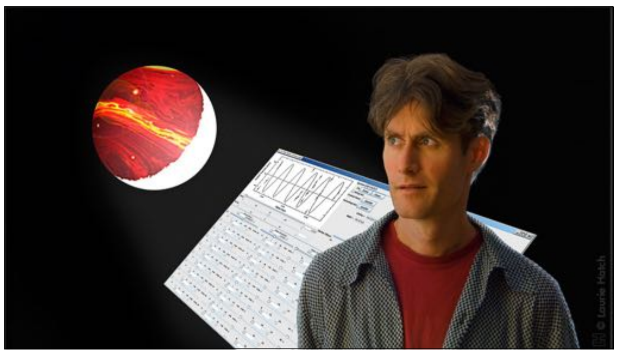


64

- These telescopes are magnificent machines, each filling a special niche in our quest to understand the universe.
- But these telescopes alone are not enough to make discoveries -- in a sense, they are just the tip of the iceberg in the story of astronomy on Maunakea.
- How does an astronomer get the chance to use these telescopes?



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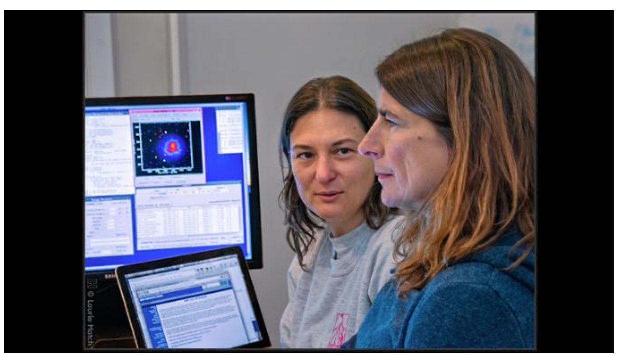
- The scientific process begins with an idea -- an astronomer who wants to address a question about stars, planets, black holes, galaxies, or some other topic.
- That astronomer and his or her colleagues will decide what data they need, and what observatory can provide those data.
- They'll write an observing proposal, a document that describes what they want to study, why it's important, and how their study will help advance the field.



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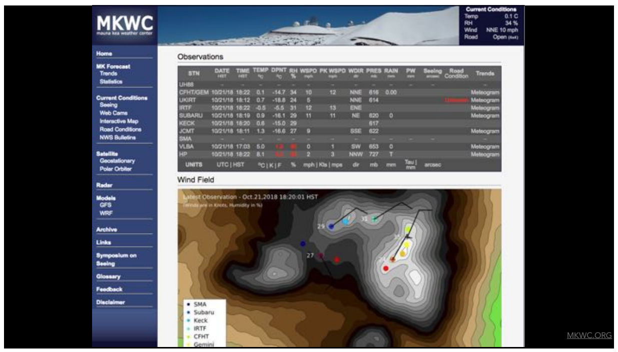
- Their request will go in with all the requests from other astronomers who want to use the telescope.
- Most telescopes receive several times more requests than they can fulfill.
- A committee of astronomers is assigned to read and rank all of the proposals based on their scientific merit, and determine which ones will receive time on the telescopes.

67

- The very best astronomers might win 20 nights a year, a huge bonanza. But many astronomers will feel glad to be awarded a single night on a large telescope. Others may receive half or even ¼ of a night -- their big chance to get data this year.
- In the weeks leading up to the run, the astronomers prepare for the run by determining exactly which targets they'll observe, when, and for how long. They make charts to ensure that they're looking in the right place.



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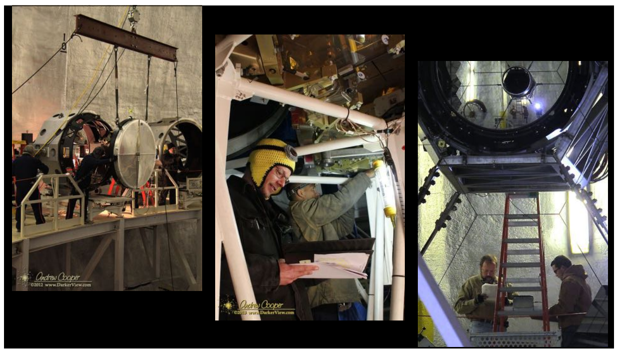
- They cross their fingers and check the weather forecast generated by a special office dedicated to predicting not only temperature and wind, but also the amount of cloud cover, the humidity, and the seeing.
- They know that if their night is ruined by clouds or a telescope problem, they'll have to apply again next year.

69

- They pack their bags and get on a jet for the long flight to Hawaii.

70

- Once they reach Hawaii, their destination is Hale Pohaku, the astronomer's dormitory on the flank of mauna kea. Here, astronomers sleep during the day while others work to support them.
- Cooks prepare their meals, housekeeping staff clean the rooms, road workers smooth the gravel road to the summit -- or plow the snow that can fall any month of the year at the summit



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- During the day, the observatory's summit staff is busy making sure that the telescopes and instruments will be ready to observe. They've reviewed the astronomer's requests for which instruments are needed and have checkout out the telescope and camera.

72

- At 5:00 the day crew finishes their tasks and departs the summit. For an while, the telescope is vacant and empty, waiting for the curtain to rise.
- Before sundown, the astronomers make the half hour drive on the bone-jarring road to the summit, breathing a sigh of relief when they reach the paved portion that carries them the final two miles across a bizarre lunar landscape to the location of their temple for the night.

73

- As the day ends, visitors also flock to the summit to watch the spectacle of the sun set from the highest point in the pacific.

74

- As the day ends, visitors also flock to the summit to watch the spectacle of the sun set from the highest point in the pacific.

75

- Once the sun is down, the visitors leave as the summit temperature drops to near freezing. At the telescope, the telescope operator opens the dome to allow the telescope to reach the same temperature as the night air.
- If the telescope is much warmer than the outside air, it will produce convective currents and air turbulence right at the mirror that will degrade the spectacular mauna kea image quality. For that reason, the daytime staff has been monitoring the predictions for tonight's sunset temperature and has set the air conditioning in the dome to bring the telescope to that temperature. For many of these observatories, electricity to run those air conditioners costs tens of thousands of dollars per month, one of their

76

- As the sky darkens, the stars come out.
- The operator slews the telescope to the first target and focuses the telescope.
- If they're using an infrared telescope, observing can start now.
- If they're observing faint targets in visible light, they wait for astronomical twilight when the sky is truly dark before starting the main science program.

77

- The astronomers will control the camera that takes the data, but the dome and the telescope are controlled by the telescope operator who site in front of a bank of monitors telling them the status of the telescope, the dome, the clouds, and the weather.
- They work a shift of several consecutive 14-hour nights on the summit.

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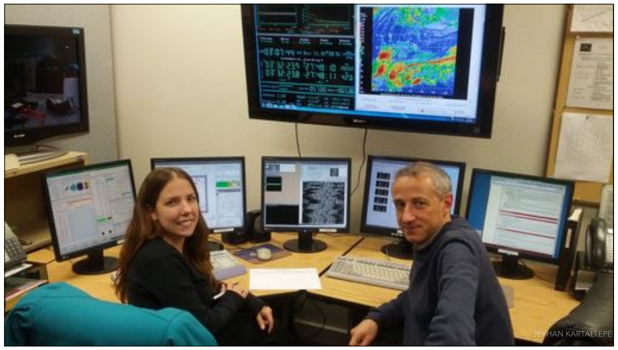
- The support astronomer is an expert on making observations who is responsible for making sure that the observers understand how to operate the instruments.
- They will remain with the astronomers until things are going smoothly, sometimes which could be a couple of hours or all night.



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- Astronomers hang out in warm control room.
- They down cup after cup of coffee to stave off the exhaustion staying up all night after a jet-lag inducing flight.
- Rarely is there an “aha” moment during the night. Many observations involve 15 minutes of frantic activity to align the telescope and start a new observing sequence, then an hour of time waiting and watching. The process of discovery will occur later, often months in the future when the astronomers have a chance to analyze their data.

80

- The astronomers constantly watch the weather, hoping that the clouds stay away.
- Any moisture on the mirror can ruin that precious layer of aluminum that reflects the photons, so the telescope operators must close the dome at the first sign of fog.
- They monitor humidity gauges, a cameras that watch for clouds.
- They may phone their friends at the other observatories for a weather report.

see https://www.gemini.edu/sciops/telescopes-and-sites/weather/mauna-kea/cloud-cam/allnightlong.html

81

- While the skies are clear, the observers chase their targets as the stars whirl across the sky, always trying to observe their targets at the high point of their arc when they can be seen through a minimum of air.

82

- If a problem occurs with the telescope, the telescope operator will consult the schedule to see which staff member is on call for the night. That person will awaken at some early hour of the morning and try to shake the cobwebs from their brain to diagnose and fix a problem.
- With luck, it’s something they can fix without having to drive 2 hours to the summit.
- Each second of observing time on these big telescopes is worth $3, so getting back on the sky is a top priority.

83

- Eventually the skies brighten as the night ends, and the telescope can no longer track the guide stars in the brightening dawn.
- The astronomers may dash outside to watch a spectacular sunrise. If so, they’ll be treated to an awesome view to the west that looks like a new mountain but is actually just the long shadow of the highest peak around.

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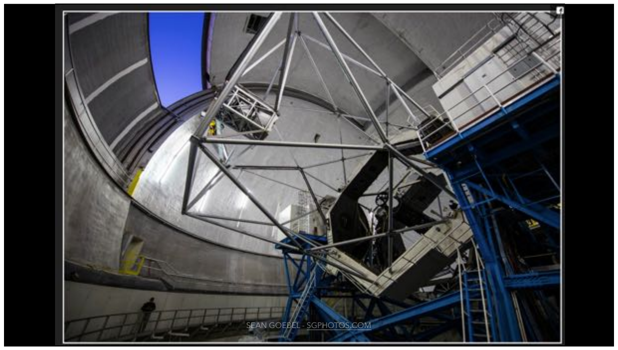
- Then they will head down the mountain to Hale Pohaku and try to convince their tired body to sleep even though the sun peaks in through the window.



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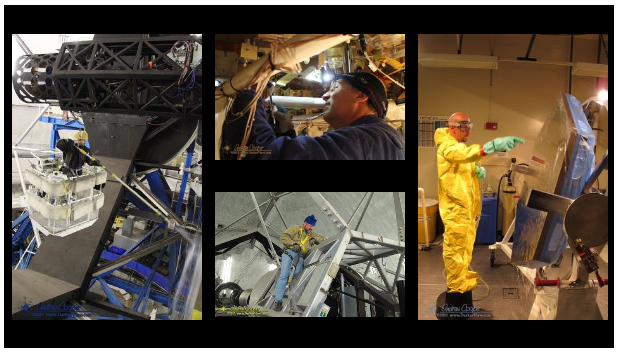
- Meanwhile, the observing assistant closes the telescope and submits their report on the night's observing, mentioning any problems that occurred during the night.
- Perhaps the instrument was having trouble focusing, or the dome was making strange noises when it turned, or the instrument computer kept crashing.



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- The early risers on the daycrew will read the nightlog and determine what the members of the day crew will be doing -- fix those problems, doing routine maintenance, or making some long-delayed improvements to the telescope system, the dome system, the air conditioner. Maybe this will be the day that the engineer can install that new high-tech wind gauge that will be able to tell the astronomers which way the wind is blowing.
- They'll work wearing oxygen masks in the thin air of the summit before it's time to prepare the telescopes for another night of work.

87

- And so the cycle continues, 365 nights a year.

(add movie)

THE PROCESS OF DISCOVERY

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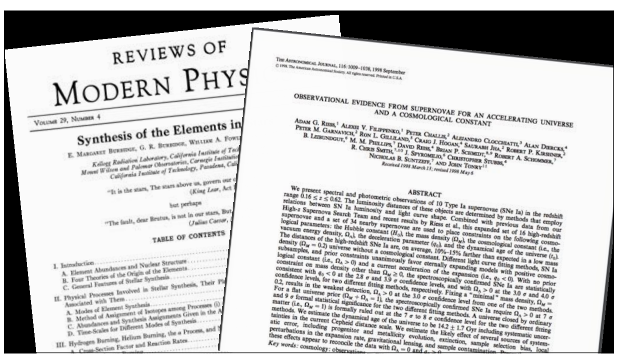
- What happens after the observing run is finished?
- The exhausted astronomers may find time for a little relaxation before taking a flight back to the mainland.



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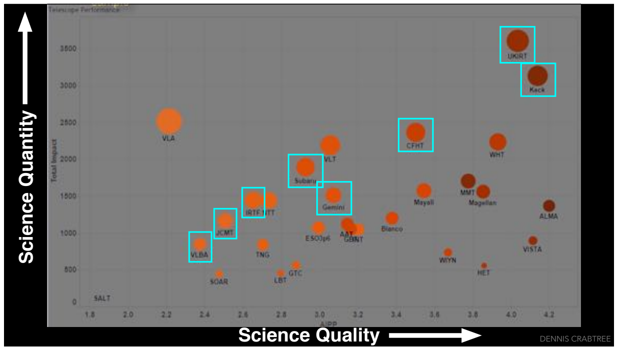
- It may take months or even years for the astronomers to analyze the data and write up their results.
- Eventually, they'll share their findings with the world through a paper published in a scientific journal.
- Those papers are the end result of the scientific process and in a way the ultimate measure of an observatories success.
- You can use that information to ask which observatories are the most scientifically productive, factoring in not only how many science papers each observatory produces but also how important those papers are based on how many times other papers cite those papers.



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- My colleague Dennis Crabtree has analyzed this and produce this plot showing the typical quality of the science from each telescope on one axis and the quantity of telescopes on the other.
- The closer to the top right corner, the better the observatory is performing.
- I've marked the observatories on Mauna Kea, and you can clearly see that many of the major contributors to astronomy worldwide come from this one mountaintop.

92

- Richard Ellis paces impatiently back and forth across a small room lined with computer terminals, trying to contain his mounting frustration. The British-born astronomer, now at Caltech, has been granted a single precious night to use one of the twin Keck telescopes, among the most powerful in the world…But things are not going right."

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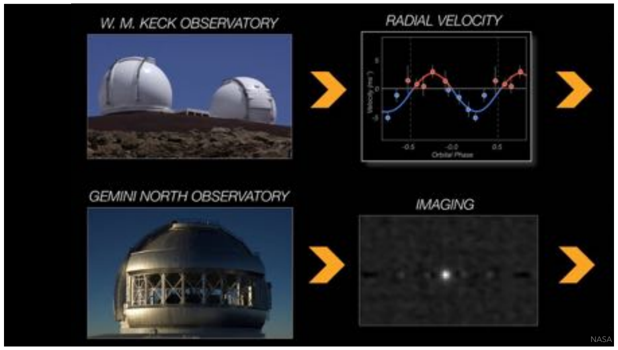
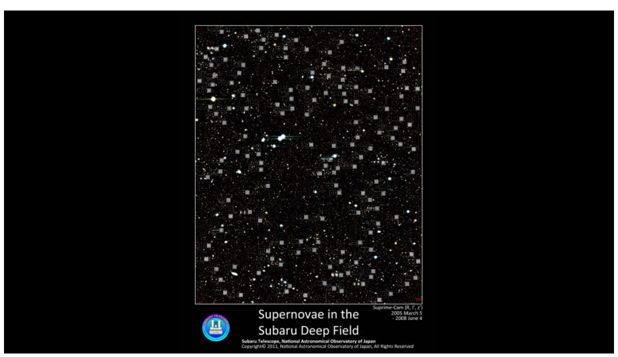


94

- The telescopes on Maunakea have had impacts on all of the most important areas of astronomy over the last two decades.
- The Keck and Gemini telescopes have been world leaders in the discovery and study of new planets around other stars by detecting the wobble in the light from stars as planets orbit them and tug on them ever so slightly.

95

- All of the large telescopes have allowed us to look deeper into space and further back in time to glimpse galaxies in the process of forming, teaching us new things about how galaxies have formed and evolved since the time of the Big Bang.



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- Astronomers also used these telescopes to observe supernovae. A common request at the observatory is to interrupt the regular observing program to observe a new supernova and determine whether it's the interesting variety called "Type Ia" that can be compared to others supernovae in distant galaxies to measure how fast the universe is expanding. Twenty years ago, most astronomers assumed that the universe must be expanding more slowly over time as the gravity from galaxies and dark matter tries to pull the universe closer together. Some even thought this expansion could someday stop and the universe could collapse back in on itself in a "big crunch.

97

- To our amazement, the supernova observations discovered that the universe is filled with a mysterious force called dark energy, which acts as an antigravity force that is actually accelerating the expansion of the universe. In 1911, three astronomers received the Nobel Prize in physics for this discovery.

98

99

- Technology has changed many aspects of our lives, and the way we do astronomy is one of them.

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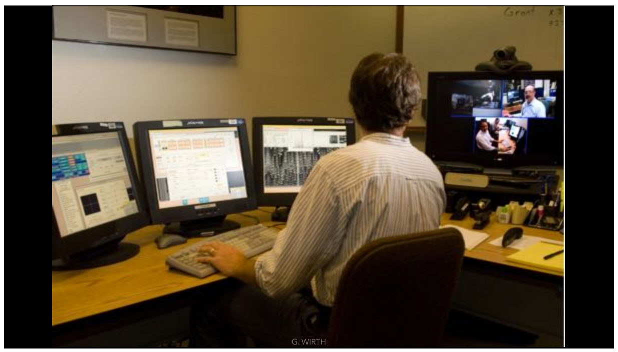
- Working in the thin air of the summit is hard on people, so observatories have been developing ways for astronomers to operate the telescopes while not even being at the summit.



101

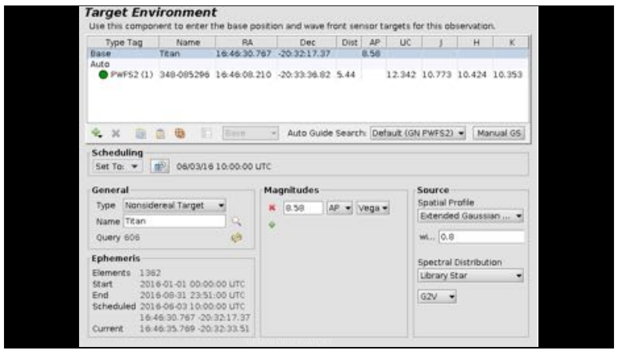
- The Keck observatory pioneered “remote observing” capability twenty years ago, with the astronomers collecting images remotely from the comfort of a control room down the mountain in the Keck headquarters in Waimea.
- There, they can walk to a restaurant for dinner and dash down the street for coffee or a late night snack during the night -- a far cry from the deprivations of the summit!

102

- And now that Hawaii has fast internet access to the mainland, astronomers don’t even need to come to Hawaii anymore, because Keck has set up remote observing stations 16 sites from California to the US east coast, and even australia.

103

- For many of us a trip to Hawaii is the chance of a lifetime, but for an astronomer who had already made the trip dozens of times, the prospect of walking down the hall to an office instead of flying across the ocean both ways is appealing.
- Some observatories are going even further by taking the observatory nighttime staff off the mountain entirely! The CFHT telescope recently upgraded their systems to be more foolproof so that the telescope operators are not even on the summit at night.



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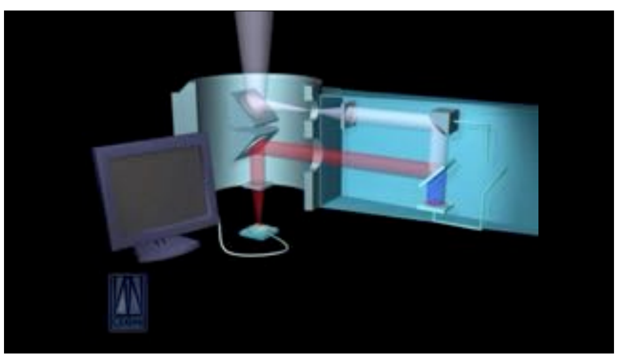
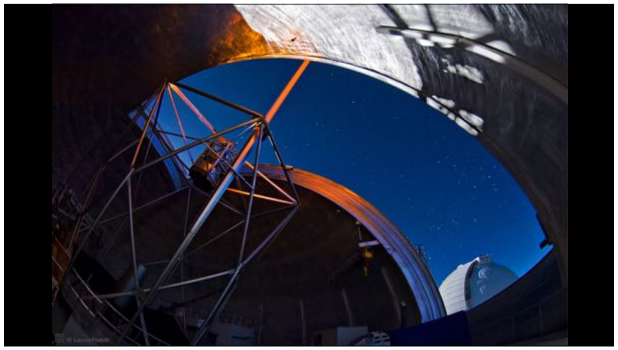
- And at many telescopes, the observer does not even take part in the observing process any longer. For these “queue scheduled” telescopes, the astronomy simply writes a set of instructions for the data they want to receive and what conditions are required -- what instrument needs to be available, what time of night is required, how dark the sky needs to be, how good the seeing needs to be -- and the request goes onto a list. The observatory staff rank the observations and execute whatever observations are appropriate at the moment. They send the data files to the astronomer at a later time.



105

- And new technologies are also changing the quality of the data astronomers can gather. The most exciting new technology -- adaptive optics -- has revolutionized the way observatories operate.
- The images of the sky seen from space are perfectly sharp, but when the light passes through earth’s fluid atmosphere it is distorted by turbulence, turning the incoming wavefronts of light represented here from from flat to distorted and blurring the images.
- In an adaptive optics system, some the blue light is diverted to a sensor that measures the distortions of the wavefronts hundreds of times each second, and then adjusts the shape of a deformable mirror to put in the exact



106

- Wouldn’t it be nice if you could arrange for a star to appear anywhere you looked? Astronomers came up with a clever solution -- they attach a giant laser to the telescope so that anywhere you look, a star appears.
- This “Laser Guide Star” system works exactly like a giant laser pointer.
- This laser pointer allows me to create point of light on a wall because the light passes through the air and reflects off the screen.
- A Later Guider Star system works the same way, because the wavelength of the light is tuned to a frequency that can be absorbed and re-emitted by sodium atoms.
- It turns out that a layer of sodium atoms exists right at the top of the earth’s

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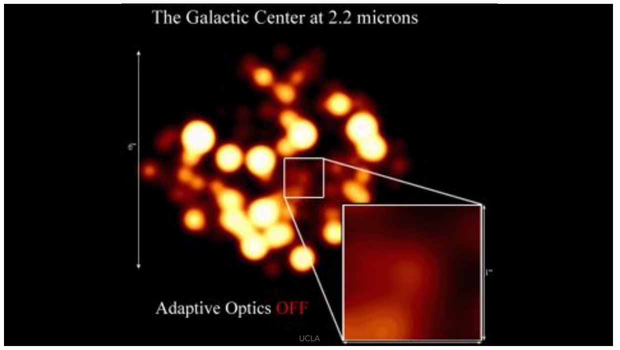
107

- Wouldn’t it be nice if you could arrange for a star to appear anywhere you looked? Astronomers came up with a clever solution -- they attach a giant laser to the telescope so that anywhere you look, a star appears.
- This “Laser Guide Star” system works exactly like a giant laser pointer.
- The pointer allows me to create point of light on a wall because the light passes through the air and reflects off the screen.
- In the case of the LGS system, the wavelength of the light is tuned to a frequency that can be absorbed and re-emitted by sodium atoms.
- It turns out that a layer of sodium atoms exists right at the top of the earth’s atmosphere, deposited there by meteoroids that burn up in the atmosphere.

108

- One of the most popular uses for this system has been to study the center of our own galaxy. Since four telescopes on Mauna Kea now have laser guide stars adaptive optics systems, On many summer nights on Mauna kea you can see multiple telescopes targeting the galactic center.



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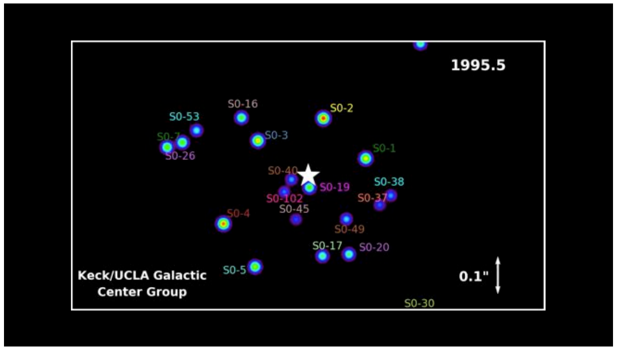
- If you look at the center of the Milky Way without adaptive optics, you can see a few dozen objects.
- But with adaptive optics, you can make out many individual stars near the center.



110

- If you watch those stars for a few years, you can even see them move!
- This movie includes 23 years' worth of data taken with the Keck telescopes.
- Notice how all of the stars are orbiting the point marked with the star.
- That tells us that something very massive is at that point. And clearly it's small, because stars can pass quite close to it and survive. And yet we see nothing. Can you guess why?
- We think these data are telling us that at this spot lives a black hole with a mass of almost 4 million solar masses!
- This is just one of the many exciting discoveries to come from the telescopes on Mauna Kea.

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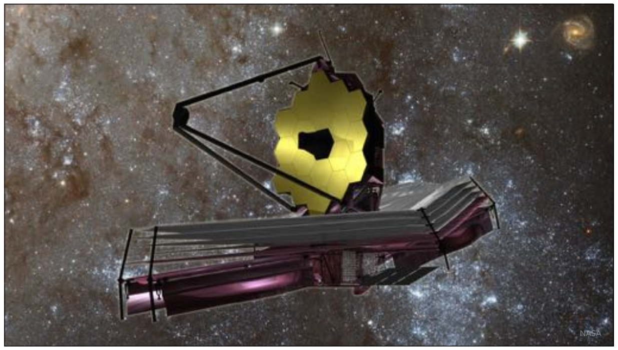

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- While spacecraft like Hubble and its eventually successor the James Webb Space Telescope are powerful observatories, the telescopes on Mauna Kea will continue to make important contributions for years to come.
- That is, if they continue to exist.

113

- The future of astronomy on Maunakea is unclear, as conflicts over the proper use of the mountaintop have emerged in the last 15 years.
- One one side are astronomers who would like to continue operating telescopes on the premier place on earth for observing the stars, perhaps build even more telescopes.

114

- On the other side are opponents of further development, some of whom even argue for the removal of the telescopes and the return of the mountaintop to its original state.

115

- Astronomers now accept that future development on the mountaintop must be very limited.
- The University of Hawaii has improved its stewardship of the mountain to protect the fragile ecosystem and the numerous cultural sites on the summit that are significant to the Hawaiian people.

116

- The recently adopted master plan calls for decommissioning and removing old telescopes, and proposes only one new telescope building for the summit: a Thirty Meter Telescope that would dwarf all others.

117

- Public hearings and court fights over whether to build the TMT have continued for several years,
- The TMT developers have been forced to make contingency plans to build their telescope in the Canary islands if they do not soon obtain permission to build atop Mauna Kea.
- The TMT is in a race against competition telescopes currently under construction in Chile to come online and make new discoveries.

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- If the TMT goes elsewhere, it will signal a turning point in astronomy on Maunakea.
- While the future is unclear, astronomers continue to flock to Hawaii for the unparalleled view of the night sky.
- By studying the stars, we learn about our own origins.
- We now understand that each of us is made of material that originated before the earth come into being. Each of us is a collection of atoms 13.8 billion years in the making that have come together for a time to form a sentient being, and will someday return to another form. You are 10% Big Bang leftovers, 17% material from stars, and 73% of you came from

119

- We came from the universe, and now we are the universe's way of studying itself.
- And Mauna Kea has been our most valuable tool for doing that.
- Mahalo.

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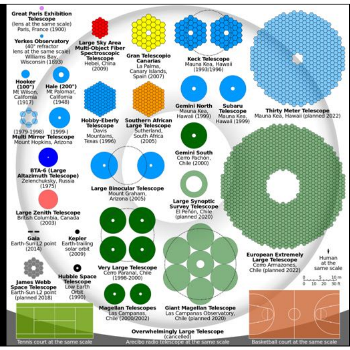

Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay, Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
(1979-1998) (1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Gemini South
Cerro Pachón, Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale