About the Inouye Solar Telescope

Inouye Solar Telescope Overview

Who

The National Science Foundation's Daniel K. Inouye Solar Telescope is the most powerful solar telescope in the world. It was built and is operated by the National Solar Observatory (NSO) – a research center operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation Division of Astronomical Sciences.

What

The Inouye Solar Telescope uses the largest mirror of any solar telescope in the world. At 13 feet (4 meters) across, it collects seven times more sunlight than any other solar telescope, producing the clearest, highest resolution images of our Sun ever taken.

When

The planning for the Inouye Solar Telescope began close to three decades ago. Construction beginning in 2010 and the first solar images were captured by the observatory in late 2019. It is expected that the Inouye Solar Telescope will be operational for at least 44 years – or four solar cycles – through to the 2060s.

Where

The Inouye Solar Telescope is located at Haleakalā Observatories site on the island of Maui, Hawaiʻi. After a lengthy worldwide search, Haleakalā was found to be the best site in the world capable of fulfilling DKIST's science objectives. At 10,000-feet elevation, and surrounded by ocean, this unique location combines dark blue skies needed to observe the faint corona of the sun, high elevation and low air turbulence of the atmosphere above the telescope.
In addition to the telescope site, the observatory has a base facility located in Pukalani. Its data center is located at the headquarters of NSO in Boulder, Colorado.

Why

We live in the atmosphere of our Sun and it is becoming increasingly important to understand and predict the behavior of this dynamic star. The Inouye Solar Telescope's primary objective is to observe magnetic fields on the Sun in order to understand its dynamic behavior. The Sun's magnetic fields are the source of solar flares and coronal mass ejections, otherwise known as space weather which can impact Earth and have a negative impact on our technology such as electric and communication networks. The Inouye Solar Telescope will resolve magnetic features on the Sun smaller than we've ever seen before, shedding new light on the drivers of space weather.

Inouye Solar Telescope's Main Mirror

At 13.9-feet in diameter, the NSF's Daniel K. Inouye Solar Telescope's main mirror, or "primary" mirror, is the first mirror that sunlight hits after it enters the telescope. The Inouye Solar Telescope's mirror collects more than six times more light than the next largest solar telescope. The telescope's mirror, coupled with its optical design, and cutting-edge scientific cameras which will capture infrared and visible light, will let scientists observe details in our Sun's features as small as 15.5 miles across. That's the same size as Manhattan Island seen from 92 million miles away!

The Inouye Solar Telescope's primary mirror was manufactured by Schott AG in Germany. It's made of 3-in thick glass called Zerodur – a specialized glass-ceramic that maintains its shape even when subjected to severe temperature changes. The curved, circular mirror weighs 3.6 tons.

After the mirror was manufactured, it was shipped from Germany to the University of Arizona's College of Optical Sciences for polishing of the glass. The final polishing effort, completed in 2015, took an estimated 80 hours a week for six months, and involved more than 50 people.

Precision was the goal in polishing this huge mirror as every bump impacts the quality of data. The mirror is polished to a surface roughness of less than two nanometers. That's about the size of a water molecule, or less than the diameter of a strand of DNA. That means, if DKIST's primary mirror was expanded to the diameter of the Earth, the biggest bump on its surface would be the size of a grain of sand!

In 2017, after polishing and 2 years safely tucked away in storage, the mirror was shipped to its final destination on Haleakalā in Maui. Once there, the next step was to coat the mirror with a thin coat of aluminum that amounts to less than 2 tablespoons. This took place in 2018 at the Air Force Maui Optical Station Mirror Coating Facility (MCF) which neighbors the Inouye Telescope, also atop Haleakalā. The aluminum coating provides a highly reflective surface required for the optical and infrared wavelengths at which the Inouye Solar Telescope will operate.

As the giant mirror moves to track the Sun across the sky from sunrise to sunset, the forces of gravity bend the large, but thin mirror. To correct this, air- and liquid-pressurized actuators push the back side of the mirror to compensate for changes to its shape. This keeps the observations as sharp and clear as possible for the scientists to learn the secrets of our sun.

The Inouye Solar Telescope's Rotating Instrument Lab

The Coudé (pronounced koō͞ˈdā) Instrument Laboratory is the "heart" of the National Science Foundation's DKI Solar Telescope. The Coudé lab is a physics lab within DKIST, and it's where the science happens. Weighing in at 150-tons the lab rotates to position highly specialized cameras as the telescope tracks the Sun across the sky. Its special design allows for studies of our Sun like none other.

Light fills this room in a truly unique way. Five scientific cameras share the sunlight that beams down from the main telescope mirror above, through an opening at the top of the room. Precisely positioned mirrors, beam-splitters, and filters split the light so that each camera receives a dedicated beam.

To preserve the quality of the light beam, it is important to keep the temperature within the Coudé lab cool and stable, with very little variation (<1 degree Fahrenheit). The lab also needs to be kept extremely clean. The Coudé Lab is a cleanroom, which means it is more than 10 times cleaner than standard air. Scientists and technicians are required to wear a full coveralls, complete with booties and a hood when working in the Lab.

Creating these precise conditions presented DKIST engineers with a challenge: The light beam must enter the lab from the telescope above, yet the Lab needs to be kept isolated from the rest of the system to maintain stable clean room conditions inside. Normal cleanrooms use glass or acrylic barriers, but these materials absorb the light we are seeking to transmit. The innovative solution to this challenge was an air knife – a barrier created by a steady, rushing stream of air. This is the first time air knife technology has been used in a solar telescope. This flow of fast-moving air separates the Coudé Lab from the conditions above, keeping the Lab clean and its temperature stable while still allowing the maximum amount of light to enter the room.

Innovative engineering, problem solving, and a novel approach, make the Coudé Lab one of a kind for ground-based solar physics research.

Follow the Photons through the Inouye Solar Telescope

The journey that sunlight makes through the NSF's Daniel K. Inouye Solar Telescope is complex. Ten mirrors guide the sunlight throughout the observatory, with each playing a vital role in delivering the sharpest images of our Sun ever taken.

The light enters the system through an opening or "aperture" in the observatory dome. The first thing that sunlight strikes, is a 13-foot (4-meter) mirror; the world's largest for a solar telescope. This mirror can adjust its shape to compensate for warping of the mirror due to gravity and thermal effects! In an unusual design for large telescopes, the light is then reflected off to the side towards the secondary mirror, following the telescope's "off-axis" design. Unlike many telescopes, the Inouye's secondary mirror is at an angle to the first rather than in the path of the incoming light. This is in an attempt to reduce as much scattered light as possible – a vital effort in observing the elusive solar corona.

The secondary mirror directs the light downwards toward the "Gregorian Optical System" which dictates the alignment of all other elements. From here, the light is fired through a system of mirrors that direct the beam through a fast-flowing jet of air, called the air knife, and into the heart of observatory – the instrument laboratory, also known as the Coudé Laboratory. The air knife makes it possible for light to enter this strictly controlled physics lab without disrupting the precise conditions (e.g. temperature) required within.

Once in the Coudé lab, sunlight can be directed to the “deformable mirror”. The surface of this extraordinary mirror changes its shape 2,000 times a second to counteract turbulence in the Earth’s atmosphere. The mirror is modified by a series of tiny pistons pushing on the surface. This ensures the light beam is as distortion-free as possible before hitting the scientific cameras.

Once the deformable mirror realigns the light, it can then pass into the Facility Instrument Distribution Optics, or FIDO. Like a traffic controller, FIDO directs specific portions of light into its respective scientific cameras, capturing the highest resolution observations of our Sun ever taken.

The Science Instruments of the Inouye Solar Telescope

The first generation of scientific instruments available at NSF’s Daniel K. Inouye Solar Telescope will observe the Sun in powerful new ways. The high-spec scientific cameras provide ultra-high-definition imaging along with new measurements of the Sun’s magnetic field, achieving a view of Sun like never before.

The Inouye telescope changes the game by providing unprecedented access throughout the Sun’s atmosphere, including the corona – the white glowing “crown” emanating from, and encircling our Sun. In addition to the high-quality observations of the surface and low atmosphere, the Inouye Solar Telescope will collect observations of the corona on a daily basis. This provides unprecedented access to this elusive region of the solar atmosphere normally only visible during total solar eclipses. These observations will, for the first time, facilitate the measurement of magnetic field strength in the solar corona.

The first images taken by the Inouye are from the Visible Broadband Imager, or VBI. The VBI captures pictures of the solar surface and low atmosphere at the highest possible spatial resolution. Built in Belfast, its ≳16Megapixel camera snaps super, high-resolution images of the

Sun’s surface and atmosphere, showing us details as small as 15 miles across. This is like being able to see Manhattan island on the surface of the Sun!

The other science instruments include the Visible Spectropolarimeter (ViSP), The Visible Tunable Filter (VTF), the Diffraction Limited Near Infrared Spectropolarimeter (DL-NIRSP) and the Cryogenic Near Infrared Spectropolarimeter, or Cryo-NIRSP. Each instrument plays a specific role in measuring the ever-changing conditions throughout the solar atmosphere, from the surface, through the corona. The instruments capture light originating from the visible and infrared part of the solar spectrum.

The instruments were designed and built all over the world. The University of Hawaii’s Institute for Astronomy are contributing the DL-NIRSP and Cryo-NIRSP instrument. The High Altitude Observatory in Boulder, Colorado is responsible for the ViSP, and the Leibniz Institute for Solar Physics, Germany designed in built the VTF. NSO leads the efforts for VBI.

Adaptive Optics – The Challenge of the Atmosphere

Telescopes located on Earth – known as ground-based telescopes – offer many benefits over their space-based counterparts. Ground-based telescopes can be significantly more complex than those in space, and can be tens of times larger, as well as lasting decades longer. The Inouye Solar Telescope has an expected lifetime of 44 years – four sunspot cycles! Ground-based observatories can also be accessed easily for repair and upgrading, unlike those in space.

The big challenge in ground-based astronomy is the Earth, the Earth’s atmosphere to be specific. Light passes unscathed from its source (in this case, the Sun) through space. However, having travelled on 99.9999% of its journey, the light beam encounters the Earth’s atmosphere. The atmosphere is full of waves and currents that interfere with the clarity of our light beam, much like water in a swimming pool might distort your view of an object at the bottom.

The Inouye Solar Telescope’s team is tackling this challenge using a process called adaptive optics. This literally means the optics – in this case, mirrors – are warped to counteract the waves, turbulence and other disturbances in our atmosphere. This is a bit like having shapeshifting goggles that make that object in the swimming pool regain its normal shape. The observatory's "Deformable Mirror" uses 1600 pistons pushing on the back side of the mirror to change its shape 2,000 times a second!

Ground based astronomy is no stranger to adaptive optics systems – this is a technique adopted by every world-class observatory today. However, adaptive optics for solar astronomy poses a whole new challenge. Solar adaptive optics was pioneered at NSO's former telescope – the Dunn Solar Telescope – by the Director of the Inouye Solar Telescope himself, Dr. Thomas Rimmele. The Inouye team continues to push the advances of adaptive optics, already planning for the next generation system for the telescope. This will use multiple mirror systems simultaneously instead of the traditional single system. The Inouye Solar Telescope is pushing the boundaries, not only of our understanding of the Sun, but of our technological applications too.

How does the Inouye Solar Telescope Resist the Heat?

Pointing a 13-foot, (4-meter) mirror directly at the Sun presents many challenges, not the least of which, is controlling the heat. Using something as small as a hand-held magnifying glass to focus sunlight is enough to burn paper, so imagine the power of focusing 4-m worth of sunlight.

Generating this tremendous amount of heat requires innovative cooling strategies to avoid damaging delicate telescope equipment and the building it lives in.

Maintaining sharp, high-quality images means the telescope's optics need to be kept at near ambient temperature; the same temperature as the surrounding environment. That's hard to do with 12kW of solar power bouncing around the telescope! Excess heat and resulting temperature changes, which can happen anywhere between the incoming light and the cameras, add distortions similar to the shimmering effect seen rising from an asphalt road on a hot day. This can severely deteriorate the quality of the telescope's images.

Three elements are responsible for crucial heat protection of the telescope and its mirrors: the coolant system, the dome, and the heat-stop.

More than seven miles of piping distribute coolant throughout the observatory. The coolant – dynalene – is partly chilled by ice, which is created at the observatory during the night. The coolant is distributed throughout the observatory systems, including the dome and the heat-stop.

The dome – the structure that encloses the telescope – is covered by thin, actively cooled plates. The plates minimize the temperature difference between the dome and the air, thus minimizing the potential "shimmering" effect where the light beam enters the telescope. In addition, the dome's shutters provide shade to specific parts of the telescope system, keeping them cool.

The first telescope mirror that sunlight touches, is carefully conditioned by cold air from behind its surface and a liquid-cooled circular ring in front. However, a major heat challenge occurs when the first mirror focuses light towards the second mirror. The focused light harnesses 12 kilowatts of solar power. That's enough power to pop a bag of popcorn in 20 seconds!

To prevent this intense beam of sunlight from damaging the telescope's components, a "heat-stop" is employed to block most of the energy. The heat-stop is placed just in front of the second mirror where the light beam is most intense. This liquid-cooled, metal "donut" allows only a narrow beam of light to pass through, eliminating more than 95 percent of the heat from the system.

In the unlikely event that the heat-stop cooling system fails, a safety cover deploys to block the light in protecting the heat-stop and secondary mirror. A separate safety cover protects main mirror and the dome is quickly closed. These and other built-in systems ensure DKIST keeps its cool.

A Year in the Life of the Inouye Solar Telescope

During normal operations, the NSF's Daniel K. Inouye Solar Telescope will be collecting about 9 terabytes of data each day. That's as much data as the entire Library of Congress, every day! Collecting and distributing that much data is a complicated task, one that takes the effort and expertise of many dedicated people.

As a solar telescope, the Inouye can only operate during the day when the Sun is in the sky. This means that there is a limit to how much observing can be done with the telescope. Twice a year, the Inouye team will invite scientists from around the globe to prepare applications to use the telescope. These applications include a host of information, including what the scientists want to observe, such as sunspots, flares, or quiet sun and which scientific instruments they need to use.

Applications are prioritized by the Time Allocation Committee. This group consists of National Solar Observatory staff and other nationwide experts who review, approve, and rank the applications.

Once the observing list has been decided, based on the accepted applications, the Inouye team tests the proposed experiment on a computer program that simulates how real telescope will behave. This ensures everything will run seamlessly and safely at the telescope. This phase of the process takes about six months to complete. At this point, the next round of applications are received and the whole process begins again.

Meanwhile, the real fun begins. Each day the Inouye Solar Telescope resident scientist(s) decide which of the approved observations can be collected on that day. They will base their decisions on the weather conditions (some observations require the clearest possible sky, others not so much), the targets (e.g. sunspots) that appear on the Sun that day and other technical considerations.

The Inouye Solar Telescope is capable of observing the Sun once it is just above the horizon. This means an early start for the telescope operators. These specially trained experts begin their day before sunrise, sometimes as early as 4:30am. Working in front of multiple computer monitors from the control room next to the Coudé instrument lab, the operators execute the “opening procedures” for the day, including finding the Sun. The telescope initially locates the Sun automatically using predictions of the Sun’s position in the sky. Operators then fine tune the precise pointing, ready for the day’s observing.

As observations are collected, they are stored in large computers and later transmitted to NSO Headquarters in Boulder, CO. Once the data is calibrated, and quality controlled by the Data Center team in Boulder, the data are made available on NSO website.
From beginning to end, the observing cycle takes 12 months, but once the scientists obtain their data, they can start answering some of the big mysteries in solar science, and helping us better understand our star, the Sun.

What’s Next for the Inouye Solar Telescope

2020 marks a very important milestone in the progress of the NSF’s Daniel K. Inouye Solar Telescope project. The project officially began construction a decade ago and there is still a lot of work to be done.

Over the next eight months, the telescope and all of its systems will continue to go through a rigorous period of integration, testing and commissioning. During this time, the Inouye team will introduce the four scientific instruments into the facility, making sure they are properly aligned, calibrated and ready for data. The “commissioning” of these scientific cameras will be an important milestone in preparing the observatory for research-quality observations later in 2020.

During this time, the system used to control the telescope, called the Observatory Control System, will also be tested. These tests will ensure every element of the observatory is behaving as expected, from the turn-on sequence used to wake the telescope up in the morning through to the shut-down sequence used at the end of the day. The many safety and emergency systems will also be rigorously tested, ensuring that the telescope will be safe to use.

Once the instruments are installed and safety testing is complete, the team will begin to take scientific data. Over the next year, the Inouye Solar Telescope will be used to collect science-quality observations, gradually increasing the complexity of how the scientific camera are used together. This process requires a lot of care and time to make sure everything works as expected. In due course, scientists from across the nation and the world will be invited to request time on the telescope, with skilled telescope operators taking pre-defined observations using complex combinations of cameras.

Although it will take some months or even years to ramp up to the full complex capability of this world-leading facility, the observations being captured by the telescope right from the beginning are already the most detailed images of our Sun that have ever been taken. The capabilities of this telescope are enormous, and throughout its 44 year lifespan, through to the year 2064, it promises to revolutionize our understanding of the Sun forever.

Why Build the Inouye Solar Telescope on Haleakalā?

Soaring nearly two-miles, or three kilometers, above the Pacific Ocean, Haleakalā is Maui Island's largest volcanic mountain and a near perfect place for solar astronomy.

Haleakalā is a high-elevation, shield volcano surrounded by ocean. This unique geography offers a site 10,023 feet above the clouds, with a clear blue sky and a stable atmosphere that is relatively free of dust.

Scientists tested hundreds of sites for the NSF's Daniel K. Inouye Solar Telescope all across the world. Compared to all other locations, including Big Bear California, the La Palma in the Canary Islands, and Sacramento Peak in New Mexico, Haleakalā proved to be best site for making solar observations, especially of the Sun's elusive corona.

Trade winds make Haleakalā a particularly special location for solar astronomy. These winds bring cool air from the northeast and provide optimal wind flow over the mountain. The winds are laminar, or smooth, with low levels of turbulence. Turbulence, caused by Earth's ever-changing weather, distorts lightrays coming from the Sun, making it harder to capture the high resolution images the Inouye Solar Telescope is known for. This distortion is what causes the twinkle of distant stars. But, the stars don't "twinkle" the same on Haleakalā.

In addition to the wind conditions, telescope site scouts found low dust levels in the air atop Haleakalā. Dust particles scatter light, making faint objects like the solar corona, difficult to see. This is especially true when contrasted to something bright, like the solar surface.

Finally, Hawaii's location at about 20 degrees north latitude means the observatory also has consistent sunlight duration.

These unique elements combine to make Maui and Haleakalā the best location where we can see and understand the behavior of our Sun and its ethereal corona.

Our Sun and Space Weather

About Our Sun

The Sun is a star, a medium-sized star. But how big is "medium"? Well, the Sun's diameter is the same length as 109 Earths lined up side by side. That's about 865,000 miles! That means that one million Earths could fit inside of our Sun. So, although our Sun is a "medium" sized star, it's LARGE by our standards on Earth. Even though it is 93 million miles away from us, our Sun is so large that its atmosphere reaches out and surrounds not only our planet, but our entire solar system! Simply put, we live in the atmosphere of our Sun. It's *our* star.

What's the atmosphere of our Sun like?

The *corona* is our Sun's atmosphere. It appears as a white glowing "crown" emanating from, and encircling our Sun. The corona is made up of plasma, a highly charged gaseous substance that is also found during lightning strikes on Earth. This super-heated gas is threaded with tangled magnetic fields which are the source of solar storms. The corona extends to nearly a million miles above the Sun's visible surface (known as its "photosphere"). The Sun's surface is a million times brighter than the corona, which makes the corona almost impossible to see from Earth. However, during a total solar eclipse, the moon perfectly blocks the Sun's surface light, allowing the corona to shine through.

What makes Inouye Solar Telescope special, is that has a coronagraph which can show us the Sun's elusive corona at any time, regardless of how our Sun, Moon, and Earth are aligned. The corona's structure is in constant motion, driven and controlled by the Sun's intense magnetic fields. The Inouye Solar Telescope will show us the corona in powerful new ways, by measuring the strengths of these fields as they change over time.

The Sun is magnetic

We live within the atmosphere of our Sun and so it's important to understand and predict changes to this atmosphere (i.e. the corona). Since these changes are driven by solar magnetic fields, it's important to study the origins of these fields and how they behave. How do they develop? How do they store and release energy? These are questions scientists seek to answer with the Inouye Solar Telescope.

When the Sun's magnetic fields become strained, huge amounts of energy is released in mere seconds. We can see these releases as a flashes of light called solar flares. In some cases, large volumes of solar plasma and magnetic fields also burst from the Sun in what is known as coronal mass ejections or CMEs. CMEs travel millions of miles, past the Earth and across the solar system. Solar flares and CMEs are some of the phenomena collectively referred to as space weather. Space weather events impact us on Earth as they have the potential to affect electricity grids, satellite communications and radio communications, amongst other things.

How does the Sun's atmosphere affect us on Earth?

Space weather is the cause of the beautiful aurora seen on Earth. But with this beauty also comes the potential for disruption. Space weather can also damage satellites and trip power grids by impacting Earth's atmosphere, as well as the structure of Earth's magnetic field. Space weather events can cause long-lasting electrical blackouts and render technologies such as GPS and radio communications unreliable. These technologies have become essential for everyday modern life. For example, emergency first responders, airplane pilots, and farmers rely on GPS. Thus, the race to better forecast and predict space weather events continues. The Inouye Solar Telescope will play a vital role in pushing our forecast capability forward. By observing the smallest changes in the Sun's magnetic field using the cutting edge science instruments of the Inouye Solar Telescope, scientists can refine the mathematical models used to predict space weather events, much like forecasting the rain on Earth. The Inouye provides observations on the same scale as the mathematical models, allowing scientists to directly compare their theories to real observations at these scales for the very first time.

Summary

We are inherently tied to our Sun. We live within its atmosphere. The magnetic Sun and its atmosphere are at the root of space weather events that impact modern day life on Earth. One of the Inouye Solar Telescope's main objectives is to study magnetic fields at the smallest scales to better explain their behavior. This will help scientists not only understand what makes our Sun and other stars "tick", but also be better prepared for Earth-impacting space weather events.