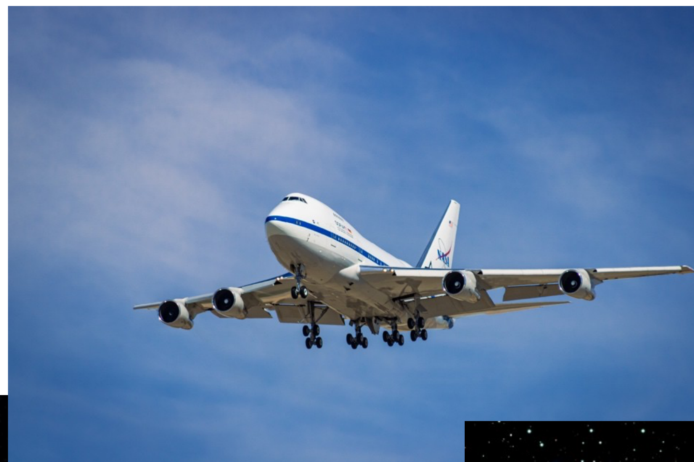
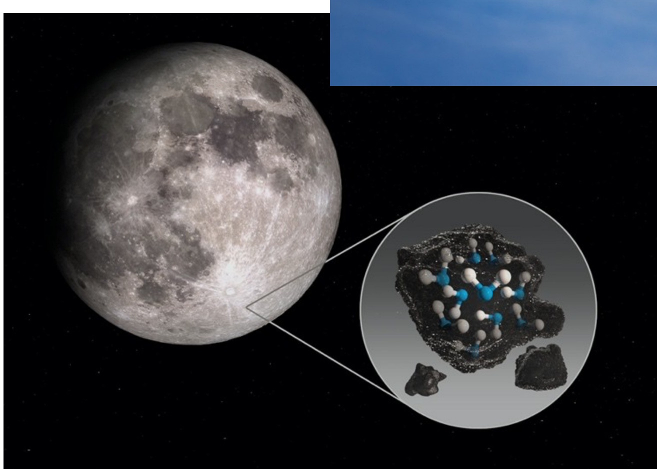
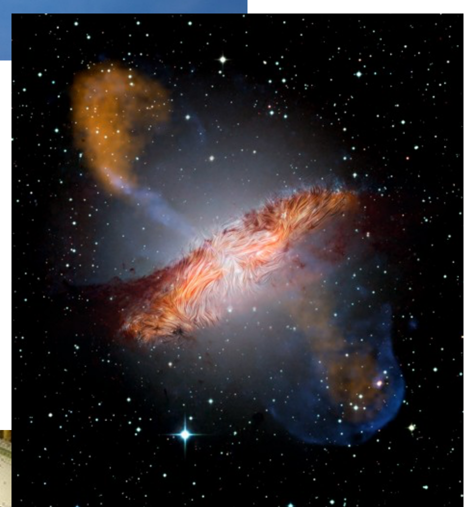
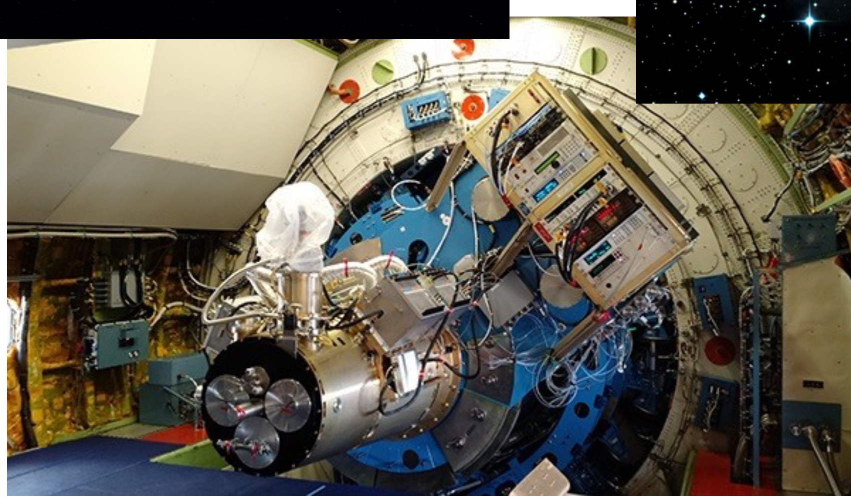
NASA Airborne Astronomy Ambassadors

SOFIA Science Overview
SOFIA Science Case Studies
4th Edition (2021)









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I. Electromagnetic Radiation

A. Visible light

Human eyes are sensitive to electromagnetic radiation with wavelengths between about 400 and 750 nanometers (frequencies between about 7.5×10^{14} and 4.0×10^{14} Hertz). That range is referred to as visible light.

B. Infrared light

Infrared light has longer wavelengths and lower frequencies than visible light. It was discovered by William Herschel in 1800 during an experiment to measure the relative strengths of different colors of sunlight (Figure 1). Physicists and astronomers consider the infrared portion of the electromagnetic spectrum to extend from a wavelength of 0.75 **microns** (750 nm, the red limit of human vision) to about 300 microns (300,000 nm).

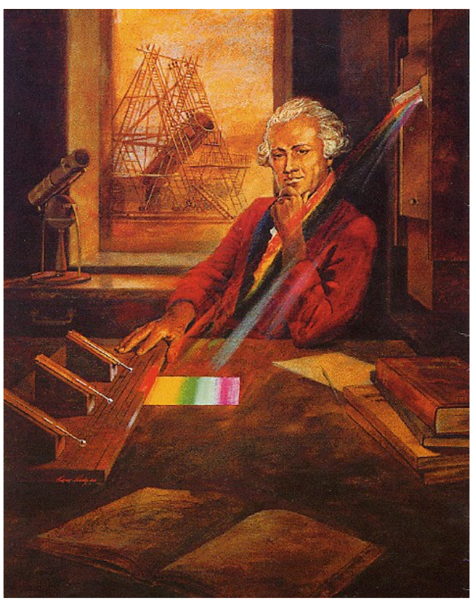


Figure 1: Depiction of Sir William Herschel discovering infrared light.
(From *Foundations*, Seeds & Backman, © 2016 Cengage Learning.)

The broad infrared range is conventionally divided into: **near-infrared** = 0.75 to 5 microns, **mid-infrared** = 5 to 30 microns, and **far-infrared** = 30 to 300 microns. The boundaries between these ranges are rather arbitrary, corresponding to various practical considerations. For example, detecting near-IR light employs techniques similar to those for visible light, the mid-IR range is where terrestrial background radiation is strongest, and the far-IR range is completely unobservable from Earth's surface due to atmospheric water vapor.

C. Blackbody emission / Wien's law

Electromagnetic radiation is produced any time a charged particle, for example an electron, accelerates. The rate of acceleration determines the frequency (and, therefore reciprocally, the wavelength) of the radiation produced.

An idealized type of radiating object that is completely opaque and therefore absorbs and emits all wavelengths of radiation with 100% efficiency is called a **blackbody**. Blackbody radiators actually glow; they are not necessarily black at visual wavelengths.

The temperature of a blackbody determines the acceleration rates of the charges within it, and thus the **spectrum** (intensity as a function of frequency or wavelength) of the radiation it produces. Lab experiments plus theoretical work determined that the peak intensity of radiation from a blackbody is at a wavelength inversely proportional to temperature. This relationship, which pertains only to blackbody emission, is known as **Wien's law** after Wilhelm Wien, the physicist who first noted it:

$$\lambda_{max} = 2.90 \times 10^{6} \text{ nm K} / T$$

For example, the Sun's surface is an almost perfect blackbody with a temperature of 5780 K. Using Wien's law, the Sun's strongest output is calculated to be at a wavelength of about 502 nanometers.

II. Astronomy

A. Solar System / Galaxy / Universe

There is a common misperception, promoted to some extent by TV & movie science fiction, that the terms "**Solar System"**, "**Galaxy**", and "**Universe**" are pretty much synonyms. Quite the contrary; that's like mixing up neighborhood, state, and continent.

The Solar System is the Sun and all the objects gravitationally attached to the Sun including Earth, Earth's sibling **planets** plus their moons, **asteroids**, **comets**, and objects in the **Kuiper Belt**. Asteroids, comets, and Kuiper Belt objects are understood to be small bodies left over from the formation of the planets. The International Astronomical Union (IAU) defines a planet as an object massive enough to have settled gravitationally into a spherical shape and also to control its orbital zone, i.e. is able to consume or eject all smaller bodies in its vicinity. The result of the refined definition of "planet" approved in 2006 was the demotion of Pluto from planet to "**dwarf planet**" and promotion of the largest asteroid, Ceres, also now defined as a "dwarf planet". The planetary zone of the Solar System, encompassed by the diameter of Neptune's orbit, is 8 light-hours across. The Solar System is one example of a **planetary system**, of which almost 5000 are now known.

The **Milky Way Galaxy,** in which our Solar System is embedded, is a collection of at least 100 billion stars plus whatever planets, moons, and other objects orbit them. In other words, the Galaxy might contain 100 billion planetary systems. The Galaxy also includes the **interstellar**

medium (ISM) composed of clouds of gas and dust between the stars that are now understood to contain raw material for the formation of new stars and planets. The visibly prominent disk of the Galaxy is about 80,000 light-years in diameter; there is evidence that a low-density spherical halo of the Galaxy extends to a radius of 200,000 light years or more. Our Galaxy is a spiral galaxy, larger than most galaxies but not a giant.

The term "Universe" refers to everything there is. Our view extends to a distance limit of about 14 billion light-years because14 billion years is the time since the **Big Bang**. Within that limit, observational samples indicate there is a total of a trillion (10^{12}) galaxies. The observable Universe might be only a tiny fraction of the entire Universe, but right now that's all we know.

B. Telescopes and observatories

Telescopes are the main tool of astronomy research. All large telescopes are **reflecting telescopes**, in which the primary optical element is a mirror. The diameter of a telescope's primary mirror determines both its light-gathering power (capability of scooping up incoming light) and its **angular resolution** (ability to distinguish details). Both powers improve with increasing diameter. Figure 2 (left panel) shows the 8-meter Gemini North visual & near-infrared telescope in Hawai`i and (right panel) the 100-meter Green Bank radio telescope in West Virginia. The largest single telescope currently used for visual and near-infrared observations is the Gran Telescopio Canarias (GTC) in the Canary Islands that is 10.4 meters in diameter. The largest radio telescope is Tianyan, a 500-meter diameter dish in China.

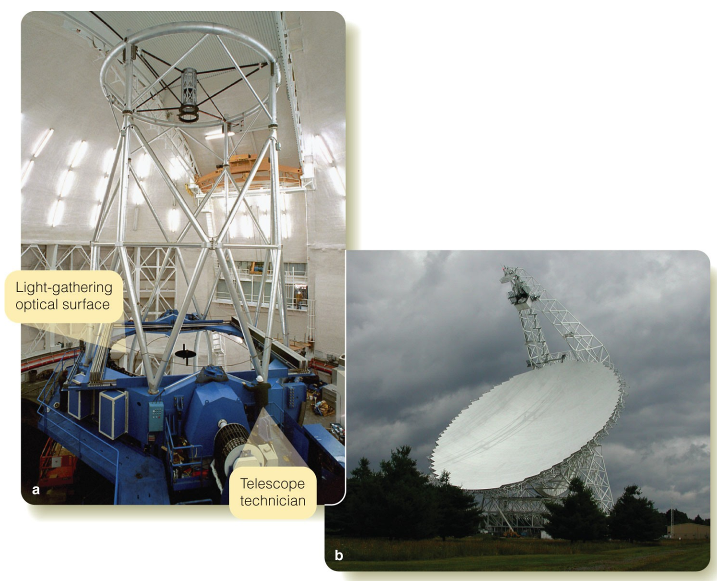


Figure 2: (a) Gemini 8-meter visual & near-infrared telescope. (b) Green Bank 100-meter radio telescope. (From *Foundations of Astronomy*, Seeds & Backman, © 2016 Cengage Learning.)

Research telescopes are generally located on mountain tops, above most cloudy weather and the turbulence of the lower atmosphere, far away from city lights. A few telescopes have been lofted into space to get completely above the atmosphere. Examples of Space Telescopes include the Hubble Space Telescope, a 2.5-meter diameter telescope that observes at near-ultraviolet, visual, and near-infrared wavelengths, and the Herschel Space Observatory with a diameter of 3.3 meter that worked at far-infrared wavelengths. **SOFIA** has a reflecting telescope with a diameter of 2.5 meters.

C. Earth's atmosphere

Earth's atmosphere is not completely transparent to all electromagnetic radiation coming from celestial sources. Water, carbon dioxide, and ozone molecules prevent some wavelengths from reaching down to even the highest mountain tops. The entire far-infrared range, between wavelengths of 30 and 300 microns, is blocked completely even from a site as high and dry as the summit of Mauna Kea in Hawai`i. Astronomers wanting to make far-infrared observations need somehow to get their telescopes above the atmosphere's water vapor layer. Space observatories are completely above the atmosphere, of course, but are also very expensive.

Astronomer Gerard Kuiper, who helped pioneer Mauna Kea as an observatory site, suggested that the best of both worlds – good infrared reception but relatively modest cost – could be achieved by an airborne observatory. Following are two plots (Figure 3) comparing the transmission (transparency) of the atmosphere (1.0 = completely transparent) from Mauna Kea at an altitude of 14,000 feet versus from SOFIA flying at 43,000 feet. Notice in the bottom panel of Figure 3 that the transmission across the far-infrared wavelength range is less than 100% and variable even from SOFIA's vantage point, but averages about 80%.

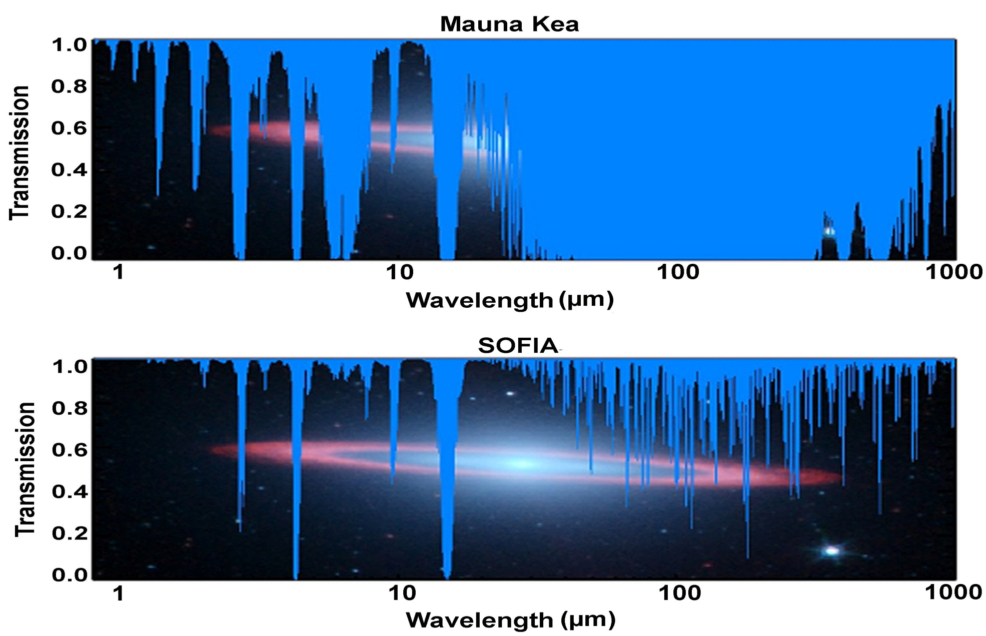


Figure 3: Comparison of Earth atmospheric transmission versus wavelength at 14,000 and 43,000 feet above sea level.

D. Infrared astronomy

The primary categories of objects normally targeted by infrared observatories are defined by the properties of infrared radiation:

(1) Low-temperature objects: The infrared range of wavelengths from 0.75 to 300 microns corresponds (via Wien's law) with temperatures from about 3000 K (e.g. objects such as cool red dwarf and red giant stars that radiate strongly at near-infrared wavelengths) down to about 10 K (objects such as dense cores of ISM clouds, radiating mostly at far-infrared wavelengths).

(2) Objects inside or behind interstellar clouds: ISM dust strongly blocks UV and visible light but allows infrared light to pass through relatively easily, more so the longer the wavelength.

(3) Large molecules: Molecules such as organic compounds have spectral features that tend to be at infrared wavelengths, corresponding to low-energy stretching and bending modes.

E. SOFIA's scientific instruments

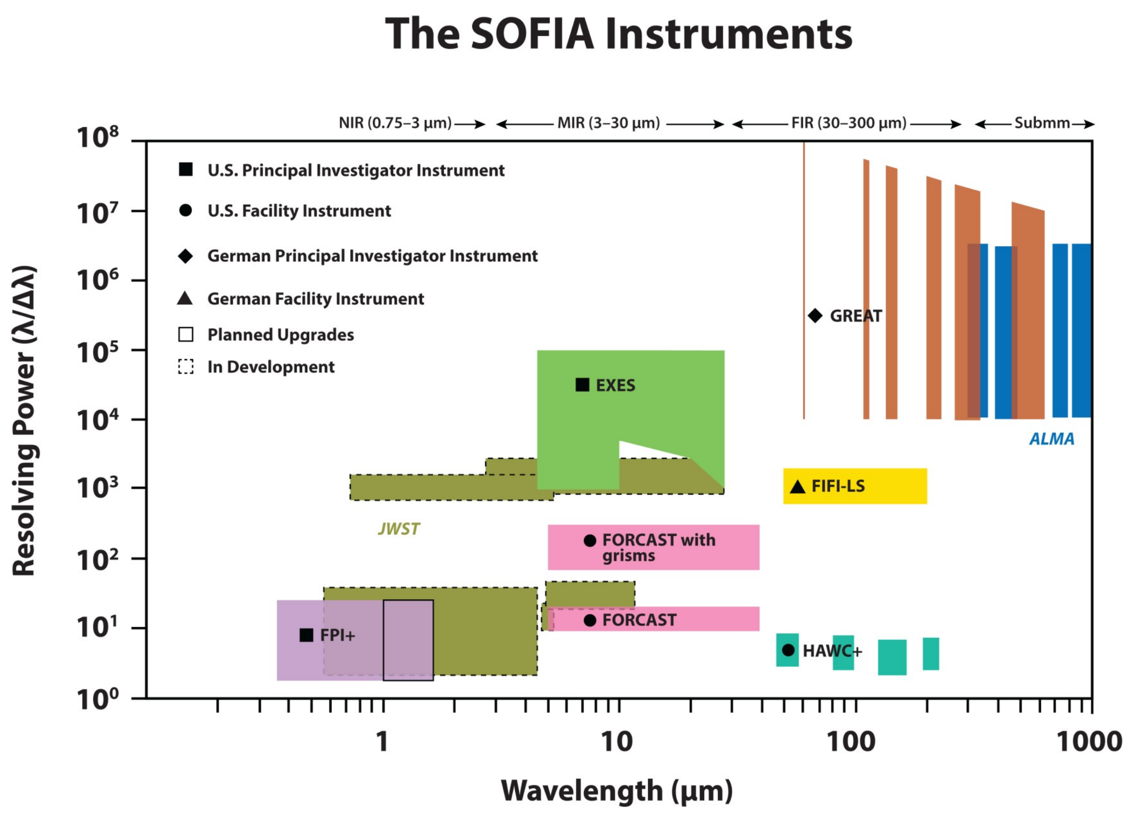


Figure 4: Spectral resolution versus wavelength "footprints" of SOFIA's scientific instruments compared with the James Webb Space Telescope (JWST; olive green) and the Atacsma Large Millimeter Array (ALMA; dark blue) radio telescope facility in Chile.

Considered together, SOFIA's instruments are capable of analyzing light with wavelengths from ultraviolet to far-infrared. Astronomical instruments fall into three general categories:

(1) **photometers** which measure the brightness of objects; (2) **imagers** which take photographs, and (3) **spectrometers** which spread light into spectra of component colors. The guider camera FPI+ can be used as a photometer; FORCAST and HAWC+ are imagers; EXES, FIFI-LS, and GREAT are spectrometers. Some SOFIA instruments combine two categories. For example, FORCAST has a selection of **grisms** ("grating prisms") giving them the ability to produce spectra of objects they have imaged. FIFI-LS in effect does the same thing: it takes images at a series of single narrow wavelengths. That instrument is called a field-imaging spectrometer.

All of SOFIA's instruments except GREAT detect radiation by relying on the particle aspect of light, i.e. converting single packets of light (photons) into electrical signals and then measuring those signals. The GREAT spectrometer is essentially a radio receiver, relying on the wave aspect of light as it detects and measures the strength of incoming electromagnetic radiation.

The vertical axis on Figure 4, **spectral resolution**, indicates the width of the smallest spectral detail that can be resolved by each instrument. For example, FORCAST with an added grism has a resolution up to about 300, meaning that when observing at a wavelength of 6 microns (6000 nm) it can detect a spectral line that is only 0.02 microns (20 nm) wide.

Glossary

accretion disk: A disk of material spiraling into (accreting onto) a central mass such as a star, protostar, or black hole.

angular resolution: Measure of the smallest spatial detail (measured in angular units) that can be distinguished by a telescope and/or imager.

asteroid: Small rocky and/or metallic object orbiting the Sun, understood to be leftover debris from the formation of the inner planets.

Big Bang: The event in which the Universe came into existence about 14 billion years ago. (More accurate names might be "Big Flash" or "Big Stretch".)

blackbody: An idealized type of radiating object that is completely opaque so that it perfectly absorbs and emits radiation of all wavelengths.

black hole: Region of space in which gravity is so strong that the escape velocity is greater than the speed of light so escape is impossible. Can form by the death & collapse of a massive star.

Circumnuclear Ring (CNR): A ring or torus of gas and dust about 5 light-years in radius surrounding the nucleus of the Milky Way Galaxy.

comet: Small icy object orbiting the Sun, understood to be leftover debris from the formation of the outer planets.

cryostat: Container of extremely cold materials such as liquid nitrogen or liquid helium. Infrared instruments are usually inside cryostats to operate at temperatures near absolute zero.

diffraction: Blurring of images caused by spreading of light waves that have encountered an edge or restricted opening.

Doppler effect: The alteration of light wavelength due to relative movement. If the distance between an emitter and a receiver is decreasing (increasing), the received wavelength is decreased (increased) relative to the emitted wavelength; this is termed a blueshift (redshift).

dwarf planet: An object orbiting the Sun that is massive enough to have settled gravitationally into a spherical shape but not massive enough to clear its orbital zone of other objects. Pluto (in the Kuiper Belt) and Ceres (in the asteroid belt) are examples of dwarf planets.

extrasolar planet (*or* exoplanet): A planet orbiting a star other than the Sun.

far-infrared (far-IR): Wavelengths from about 30 to about 300 microns.

galaxy: A large, gravitationally bound assemblage of stars and interstellar material. We live in the Milky Way Galaxy.

globular cluster: Dense sphere-shaped star cluster containing 100,000 or more starsbout 150 globular clusters are satellites of the Milky Way Galaxy.

grism: A “grating prism”, an optical device that can be installed into an imager to transform the instrument into an imaging spectrograph.

imager: A type of scientific instrument; a digital camera with an array of pixels (picture elements).

interstellar medium (ISM): Gas and dust between the stars.

Kelvin (K): Temperature scale with Centigrade degrees and zero point at absolute zero, -273ºC (-460ºF).

Kuiper Airborne Observatory (KAO): NASA’s airborne observatory from 1975 to 1995; SOFIA’s predecessor. It carried a 36-inch (0.9-meter) telescope.

Kuiper Belt: A collection of small bodies orbiting the Sun beyond the orbit of Neptune. Pluto was the first Kuiper Belt object discovered. Other bodies orbiting in that zone were discovered starting in 1992.

light curve: Plot of brightness versus time of a variable object such as a star being occulted.

light-year: Unit of length equal to the distance light travels in one year; about 6×10^{12} (trillion) miles = 10 trillion kilometers.

mare (*plural* maria): (pronounced ‘mah-ray’): (Latin for “sea”.) One of the large dark features on the Moon’s surface composed of ancient lava flows.

micron: Unit of length equal to 10^{-6} meters or 1000 nanometers.

mid-infrared (mid-IR): Wavelengths between about 3 and 30 microns.

Milky Way Galaxy: The galaxy containing our Solar System; a spiral galaxy with a visible disk about 80,000 light-years in diameter that contains more than 100 billion stars plus their respective planets

near-infrared (near-IR): Wavelengths between about 0.75 and 3 microns.

nebula: Cloud in space, usually composed of a mixture of gas and dust.

nucleosynthesis: Production of chemical elements by nuclear fusion reactions inside stars or during supernova explosions.

occultation: Blocking of a background object by a foreground object that is larger in apparent size.

peer review: The process by which a scientific paper is critiqued by experts, often anonymously, and accordingly revised before it can be published.

photometer: A type of scientific instrument that precisely measure the brightness of a target object. Some photometers contain an imager (array camera).

pixel: Single picture element of a digital image.

planet: An object orbiting the Sun that is massive enough to have settled gravitationally into a spherical shape and also massive enough to have cleared its orbital zone of other objects.

planetary nebula: Shell or cloud of gas expelled during the death throes of an approximately solar-mass star. Has no connection to planets other than its appearance in a small telescope.

planetary system: A group of planets orbiting a star. Our Solar System is an example of a planetary system. Almost 5000 planetary systems have been discovered to date.

reflecting telescope: A telescope with a mirror as its primary optical element. SOFIA carries a reflecting telescope.

representational color (*a.k.a.* false color): Color-coding of data to represent a property or properties of an object other than its actual visual-wavelength color.

Sagittarius A* (Sgr A*): Point source of X-rays and radio energy at the very center of the Milky Way Galaxy, understood to be the accretion disk around a supermassive black hole.

SOFIA: The Stratospheric Observatory for Infrared Astronomy, a joint U.S. & German scientific facility composed of a modified Boeing 747SP aircraft carrying a reflecting telescope with an effective diameter of 2.5 meters (100 inches).

Solar System: The Sun and all the objects gravitationally attached to the Sun, including Earth, Earth's sibling planets plus their moons, asteroids, comets, and Kuiper Belt objects.

spectral line: Feature in a spectrum caused by absorption or emission of light by a specific type of atom or molecule.

spectral resolution: A measure of the smallest detail in a spectrum that can be distinguished by a spectrometer.

spectrometer (spectrograph): A type of scientific instrument that measures the intensity of light in a spectrum as a function of wavelength or frequency. Some spectrometers contain an imager (array camera).

spectrum (*plural* spectra): A display of light spread into its component colors, or a graph of such a display showing intensity of light versus wavelength or frequency.

supernova: Explosive death of a massive star.

supernova remnant: Expanding cloud of gas and dust produced by a supernova.

Universe: Everything that exists. The observable Universe, which may be only a small fraction of the entire Universe, is estimated to contain 1 trillion (10^{12}) galaxies.

volatile: Substances that are relatively easily vaporized, for example water.

white dwarf: A hot, small, dense stellar object that remains after the death of a star with approximately the Sun's mass.

Wien's law: The mathematical relationship between the temperature of a blackbody and the wavelength at which its emission is most intense.

SOFIA Science Case Study: Pluto Occultation
Chasing Pluto's Shadow

Before reading, review the following key terms (Glossary, pages 8-11):
diffraction, dwarf planet, Kuiper Belt, light curve, occultation.

Background: Pluto was discovered in 1930 and became known the 9th **planet** in our **Solar System**. However, Pluto's label as a planet was later questioned. Lowell Observatory in Flagstaff, Arizona, hired amateur astronomer Clyde Tombaugh to observe a particular section of the sky to search for a new planet. Tombaugh was using calculations that pointed to the location of an object that was thought to be disturbing Neptune's motion. Tombaugh did find Pluto, but the measurements of Neptune's deviations were later found to be incorrect. Neptune's orbit is actually not being influenced by an unknown large mass in the outer Solar System. Thus, Pluto's discovery turns out to have been a lucky accident.

For more than 60 years, Pluto was included in the list of planets memorized by students. Eventually, astronomical observations were improved by new technologies. More objects were found orbiting in the same zone as Pluto. In fact, there is an entire belt of small objects beyond Neptune similar to the **asteroid** belt between Mars and Jupiter. Both belts are composed of remnants of planet construction material. The outer debris belt is named the **Kuiper Belt** after Gerard Kuiper, the astronomer who predicted its existence.

By the turn of the 21st century, hundreds of objects had been found in the Kuiper Belt, some of them almost as large as Pluto. In 2006, astronomers attending an international gathering decided to redefine the term "planet". Pluto was reclassified in a new category of **dwarf planet**. A dwarf planet is large enough for its gravity to squeeze it into a spherical shape. But, a dwarf planet is not large enough to clear its orbital zone. In contrast, Earth and the other major planets all have gravitational pulls strong enough to consume or toss away objects in nearby orbits.

Studying an object as small and far away as Pluto is not easy. One especially effective way is to wait for Pluto to move in front of a background star. When Pluto (or any other Solar System object) passes in front of a star, it blocks the light of that star. This is called an **occultation**, and some of the foreground object's properties can be determined by the details of how it occults (blocks) the background star. For example, Uranus's rings were discovered during observations of a stellar occultation from **SOFIA's** predecessor, the **Kuiper Airborne Observatory** (**KAO**), in 1984.

Another important measurement made possible by occultation observations is detection of an atmosphere. An occultation **light curve** (plot of brightness versus time) produced by a Solar System object with an atmosphere differs noticeably from one produced by an object with no atmosphere (Figure 1). An occultation with relatively gradual blocking and unblocking of the stellar light (Figure 1, right panel) shows that the foreground object has "soft edges", meaning an atmosphere. KAO observations in 1988 confirmed earlier ground-based measurement indicating that Pluto has an atmosphere.

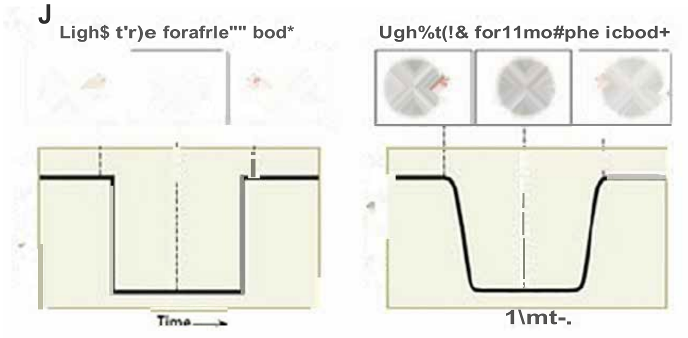


Figure 1: Light curves showing the difference between a stellar occultation by a body without (left) and with (right) an atmosphere. The light curve of a body with an atmosphere has less steep slopes because the background star's light is cut off and then recovers relative gradually. The body with an atmosphere has, in effect, a "soft" edge. (Image credit: *Astronomy Magazine*/Roen Kelly)

Previous Research: In 2011, Michael Person of MIT and Ted Dunham of Lowell Observatory were awarded time on SOFIA to observe Pluto occulting a star. Michael is a Pluto expert and Ted is an expert in occultation observations.

SOFIA's mobility let the researchers reach a position near the center of the occultation shadow track over the eastern Pacific (Figure 2). The Person team especially wanted to observe the "central flash", a small increase in brightness lasting just a few seconds in the middle of the occultation. During the central flash the background star illuminates Pluto's entire atmosphere as a bright ring. The detailed characteristics of the central flash give information about the structure of Pluto's atmosphere. For example, layers of haze lying more on one side of Pluto than another would make the central flash not symmetric. The Person team was able to get good data on the 2011 occultation and detected a weak central flash (Figure 3).

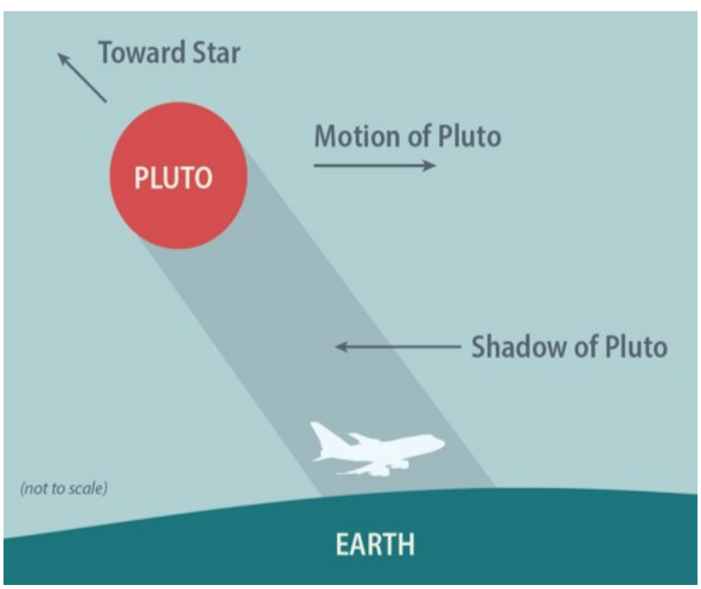


Figure 2: Diagram showing the relationship between Earth, airborne observatory, Pluto, and the background star during a stellar occultation observation. (Note: Objects in the figure are not to scale.)

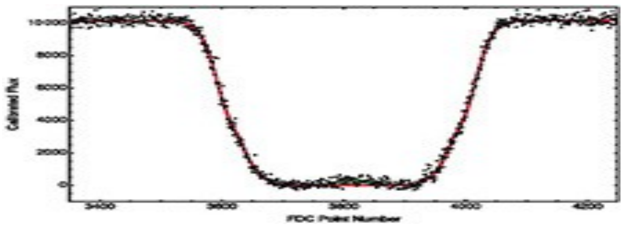


Figure 3: Pluto stellar occultation light curve from 2011 showing a weak central flash. (The central flash is the temporary slight increase in brightness in the middle of the light curve.)

The Target: Astronomers calculated that on June 29, 2015, Pluto would occult a relatively bright star. The track of Pluto's shadow in 2015 was predicted to cross the southwestern Pacific near New Zealand (Figure 4). Conveniently, SOFIA would already be in New Zealand at that time as part of the observatory's regular annual visit to the Southern Hemisphere. Thus, SOFIA would be the only large observatory that could be in the right place at the right time to gather occultation data. In another lucky coincidence, the 2015 occultation event would be less than three weeks before NASA's New Horizons spacecraft fly-by of Pluto. This would allow SOFIA to observe over-all properties of Pluto's atmosphere to provide context for later detailed measurements by New Horizons.

Figure 4: Predicted track across Earth of Pluto's 2015 stellar occultation shadow. The central solid line crossing New Zealand shows the path of the shadow's center. The outer two solid lines show the edges of Pluto's shadow. Note that Pluto's diameter is about the same size as Australia. The dashed line to the north shows the limit of uncertainty of the shadow track's position months before the date of the occultation

Instrument selected: Amanda Bosh, Michael Person's MIT doctoral student, proposed to follow up the 2011 Pluto occultation measurements with a SOFIA flight to observe the 2015 event. Amanda decided to use a combination of the HIPO and FLITECAM instruments (Figure 5). An observatory's scientific instruments are devices such as **photometers**, **imagers** (cameras), and **spectrographs** that attach to the telescope and analyze the light it gathers. HIPO is a photometer and FLITECAM is a combined imager and spectrograph. (For more information about SOFIA's instruments, see SOFIA Science Overview section II.E.

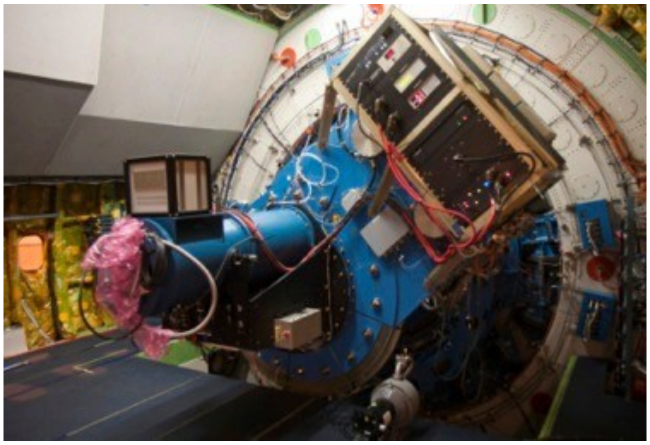


Figure 5: The FLITECAM and HIPO instruments shown mounted together on SOFIA's telescope. FLITECAM is the blue cylinder and HIPO is the black box below it.

FLITECAM and HIPO are the only two instruments that can be mounted on the SOFIA telescope together, an arrangement that increases the range of wavelengths which can be observed. This is important because the effect of atmospheric gases on light varies with wavelength. Thus, observing an occultation at several wavelengths yields more information about the foreground object's atmospheric composition and density.

Also, HIPO detects the shortest wavelengths of any SOFIA instrument and FLITECAM detects the next shortest wavelength band. Due to the optical effect called **diffraction**, measurements at short wavelengths provides the sharpest, most detailed images and light curves. Choosing the HIPO and FLITECAM combination on SOFIA for their Pluto occultation observations therefore gave Amanda's team the best chance to measure details of Pluto's atmospheric properties and structure.

Results and Interpretation: On June 30, 2015, SOFIA departed from its base at Christchurch, New Zealand. Amanda, Michael, and some of their teammates were onboard, ready to observe Pluto's stellar occultation.

There was plenty of suspense because, to observe the important central flash, SOFIA had to be located within about 100 kilometers (60 miles) of the center of Pluto's shadow. But, the position of Pluto's shadow track was not known that accurately. So, last minute adjustments to SOFIA's flight path were needed, based on fresh measurements of Pluto's position in the sky. After SOFIA had already taken off, other teammates were using a telescope in Arizona to take images of Pluto and the star it would be occulting. Those images were relayed to yet more teammates at MIT who used those data to make new calculations of where Pluto's shadow would cross Earth. The MIT group called that information via satellite phone to Amanda and Michael on SOFIA.

Amanda and Michael were able to analyze their data while still in flight on SOFIA. They used special software to measure the brightness of Pluto plus the star it was occulting to produce a light curve (Figure 6).

Amanda's team compared the 2015 light curve with the observations made in 2011 (look back to Figure 3). The starting and ending slopes of the 2015 light curve (Figures 6 & 7) were more gradual than in 2011 and the 2015 central peak was stronger. Also, the slopes of the short wavelength light curves were steeper than those of longer wavelengths. Amanda and Mike's interpretation of these observations was that Pluto had a thicker atmosphere in 2015 than in 2011, with a noticeable haze layer. That is surprising because Pluto was farther from the Sun in 2015. Pluto would get colder with increasing distance from the Sun. As the dwarf planet cooled, atmospheric gases should freeze to become snow and ice on the dwarf planet's surface. So, the scientists expected the atmosphere would be thinner in 2015 than in 2011, not thicker.

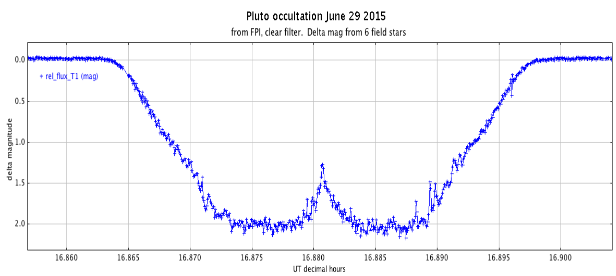


Figure 6: Pluto stellar occultation light curve from 2015 showing effects of Pluto's atmosphere, including a strong central flash. The total length of the occultation is slightly less than 2 minutes. These data are from the FPI+ camera using a filter passing most of the red part of the visual wavelength band.

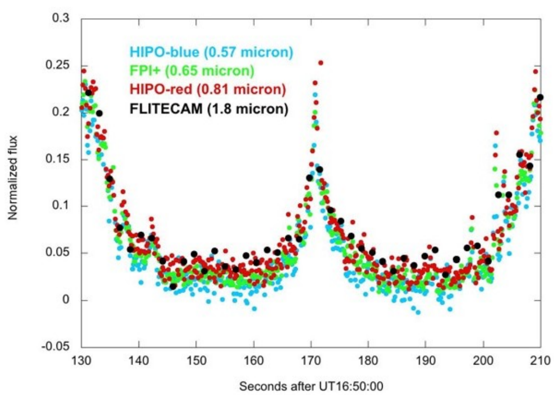


Figure 7: Combination of four 2015 Pluto occultation light curves measured through filters centered at wavelengths of 0.57, 0.65, 0.81, and 1.8 **microns**. The visual light curve (0.57 micron, blue dots) has a steeper slope than the near-infrared light curve (1.8 microns, black dots) at the start and end of the occultation. This is evidence of a haze that scatters and blocks visual light more than infrared light.

A few weeks after the SOFIA flight, the New Horizons spacecraft observed Pluto and sent back images showing Pluto is geologically active. Pluto's atmosphere may be maintained and replenished by occasional volcanic venting from inside the dwarf planet. SOFIA's observations supported these results from New Horizons because they show that Pluto's atmosphere varied in density in just a few years.

Additional resources:

Magazine article about the SOFIA 2015 Pluto occultation observations flight:
http://www.skyandtelescope.com/astronomy-news/sofia-dashes-into-plutos-shadow-07032015/

Video about the 2015 flight:
https://www.youtube.com/watch?v=jzXsg8Fnags

SOFIA Science Case Study: "First Light" Image of Jupiter
Jupiter, a Cool First Target

Before reading, review the following key terms (Glossary, pages 8-11):
blackbody, imager, pixel, representational color, Wien's law.

Background: Water vapor in Earth's atmosphere blocks most infrared light from reaching the ground. Astronomers who want to make infrared observations must somehow get their telescopes above the atmosphere's water vapor. Locations on mountains such as Mauna Kea in Hawai`i can improve infrared observing. However, some infrared light cannot be received even at the tops of mountains. On the other hand, space observatories are completely above the atmosphere but are extremely expensive. (Read SOFIA Science Overview section II.C for more information about Earth's atmosphere and infrared light.)

Astronomer Gerard Kuiper, who helped pioneer Mauna Kea as an observatory site, suggested that the best of both worlds – good infrared viewing but relatively modest cost – could be achieved by building an airborne observatory. **SOFIA** is the newest in a series of NASA infrared telescopes housed in airplanes, able to operate above almost all of the atmosphere's water vapor. SOFIA's telescope is carried in a Boeing 747SP jet airplane to operate at altitudes of 37,000 to 45,000 feet.

The Target: In early 2010, the SOFIA program was preparing for the observatory's first science flight. Astronomers refer to a telescope's inaugural observations as its "First Light". SOFIA's scientists needed to decide which object would be most appropriate to observe on that special occasion.

SOFIA Project Scientist Pam Marcum and Education & Public Outreach Director Dana Backman proposed that the observatory's first celestial target should be the **planet** Jupiter for three reasons: (1) Jupiter would be high in the evening sky during spring 2010 and therefore easy to observe. (2) Jupiter is extremely bright at both optical and infrared wavelengths. (3) Data collected from even short test observations could still provide scientifically interesting results. The SOFIA scientific staff agreed, so Jupiter it was.

Previous Research: When gas giant planets such as Jupiter are studied at visible wavelengths, we are limited to seeing only light reflected from the top of the atmosphere's clouds. However, those clouds are partly transparent to infrared radiation. Therefore, SOFIA can see past the upper layers of clouds and into the deeper layers of the planet's atmosphere.

Infrared observations of Jupiter in the 1960s from NASA's first airborne observatory, the Lear Jet, revealed that the planet gives off about twice the energy that it receives from the Sun. Based on those observations, astronomers produced mathematical models of the planet's interior. The models indicated that the heat flowing from Jupiter is energy that was trapped deep inside when the planet formed. The models also predicted that most of Jupiter's infrared radiation should be coming about equally from all locations on the planet. Researchers wanted to test the models of Jupiter's interior by making more detailed infrared images of the planet.

Instrument Selected: Every object produces a variety of electromagnetic radiation. The wavelength of strongest output of a glowing opaque object (termed a **blackbody**) such as Jupiter is determined by the temperature of the object. The relationship between temperature and a blackbody's wavelength of strongest output is called **Wien's law**. According to Wien's law, Jupiter's temperature of 152 **Kelvin** (152 K) means that the planet gives off radiation most strongly at wavelengths in the range of 25 to 40 **microns**. Those wavelengths are at the border between the **mid-infrared** and **far-infrared** ranges. (Read SOFIA Science Overview section I.C for more information about blackbody emission and Wien's law.)

SOFIA's scientific instruments are devices that attach to the telescope and convert infrared radiation from celestial sources into electrical signals. Those signals are easily manipulated and stored as digitized (numerical) data. This is basically the same process as inside an ordinary digital camera.

The FORCAST mid-infrared **imager** (Figure 1) had already been chosen as SOFIA's First Light instrument because it was among the first of SOFIA's instruments ready to fly. Also, as an imager it is simpler and easier to use than other types of instruments. Finally, FORCAST is designed to detect infrared light with wavelengths between 5 and 37 microns. Thus, it was the ideal instrument to produce the first-ever images of Jupiter at wavelengths of the planet's strongest output.

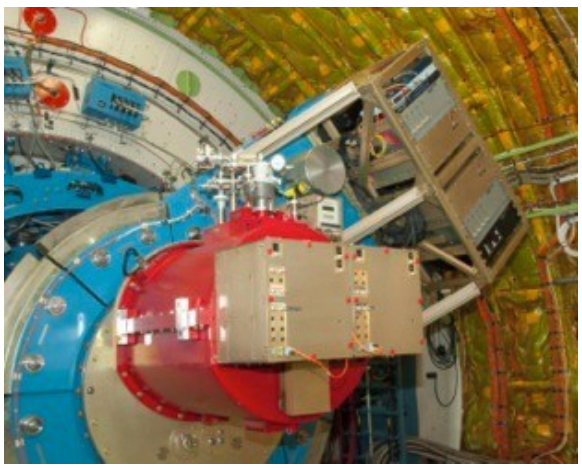


Figure 1: The FORCAST (Faint Object infRared Camera for the SOFIA Telescope) imager consists of the red cryostat (cold container) plus gold electronics boxes shown here mounted on SOFIA's telescope.

FORCAST's digitized images are stored as numerical values of an array of **pixels** ('picture elements'). Scientists can then display those data by selecting **representational colors** (also called "false colors") that we can see, representing infrared colors that we cannot see. This is a bit like Google Translate: Information we can't process, in a language we don't know, is transformed into information we can process, in a language we know.

Results and Interpretation: SOFIA's First Light flight was May 26, 2010. The researchers onboard included two of the people who designed and built FORCAST, astronomer Terry Herter and engineer George Gull. Accompanying them was SOFIA staff scientist Jim De Buizer.

The team made images of Jupiter at three wavelengths: 5.4, 24, and 37 microns (Figure 2). The 37 micron images of Jupiter from SOFIA were all new information for astronomers. After

SOFIA landed, Jim combined the images of Jupiter made by FORCAST at those three wavelengths. He chose a representational color scheme such that 5.4 microns was displayed as blue, 24 microns as green, and 37 microns as red (Figure 3). If all three wavelengths were bright in a particular area of Jupiter, the combination would appear white. (Recall that mixing light is not the same as mixing paint. Red, green, and blue digital colors in a digital image combined in equal intensities create white.)

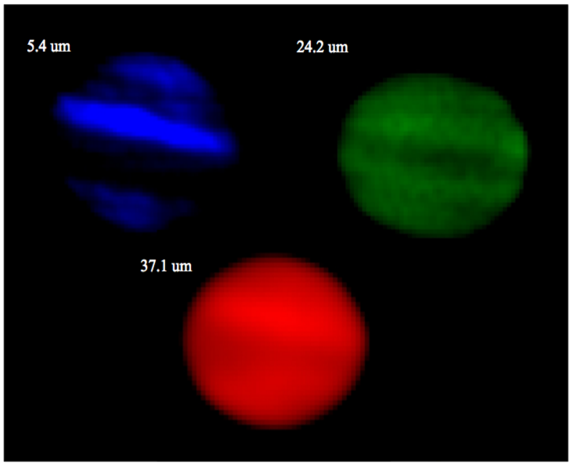


Figure 2: Jupiter images at 5.4, 24, and 37 microns obtained by the FORCAST imager during SOFIA's "First Light" flight. Component pictures of Jupiter at the three wavelengths are shown with the chosen representational color scheme.

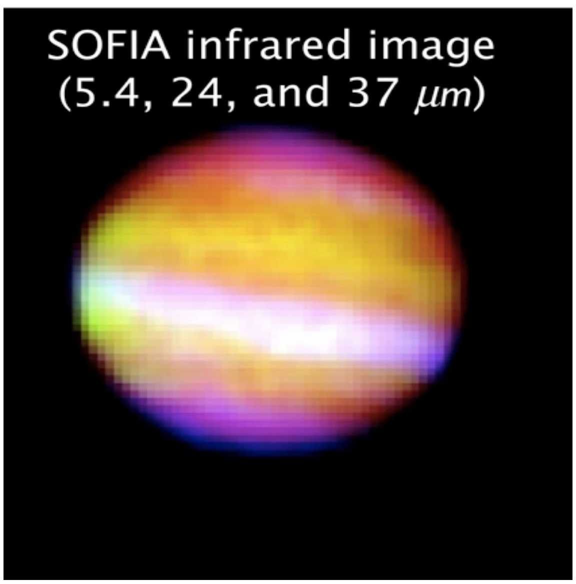


Figure 3: Representational color image of Jupiter composed of the sum of component images at three mid- and far-infrared wavelengths. The brightest white region, emitting infrared radiation strongly at all three wavelengths, is the South Equatorial Belt.

The horizontal stripe just below Jupiter's equator appears white in the composite image. This means that Jupiter is sending out strong radiation at the location of that stripe at all three wavelengths observed. (Look back to Figure 2.) Other locations on Jupiter are not giving off infrared radiation as intensely as those latitudes just below the equator.

As noted above, astronomers had made model calculations that predicted Jupiter's internal heat should "leak" out approximately evenly all over the planet. But, the SOFIA FORCAST data showed more clearly than previous observations that Jupiter's interior heat is coming out mostly at certain special latitudes.

Figure 4 is a diagram showing Jupiter's latitude zones and. belts. Zones are regions of cold, high ice crystal clouds that are white at visible wavelengths and dark at infrared wavelengths. Belts are regions where we view deeper into warm regions of Jupiter's atmosphere. The location of Jupiter's strongest infrared radiation observed by SOFIA, the bright white stripe in Figure 3, is the Southern Equatorial Belt.

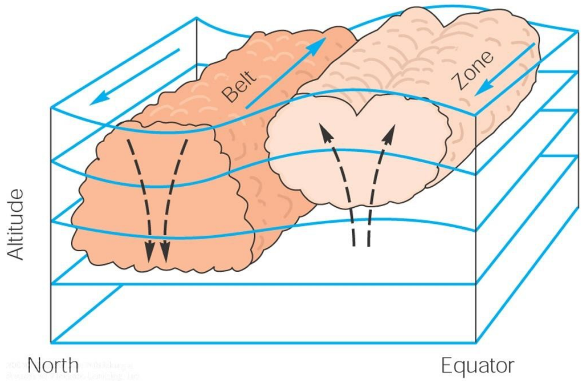


Figure 4: Jupiter's latitudinal belts and zones. At belt latitudes we can see deeper into Jupiter's atmosphere, to warmer material. (Adapted from *Horizons*, Seeds & Backman, © 2018 Cengage Learning.)

The Southern Equatorial Belt appears dark reddish-brown at visible wavelengths (Figure 5). That color may be due to organic molecules cooked up deep inside Jupiter. What scientists don't know yet is why the zones and belts are located where they are, and whether they are shallow or deep structures in Jupiter's atmosphere.

Figure 5: Visual-wavelength image of Jupiter taken approximately at the same time as the SOFIA First Light image. The darkest reddish-brown zone corresponds with the infrared-bright (white) stripe in the SOFIA FORCAST data (Credit: Anthony Wesley).

Additional resource:

The original NASA news release regarding SOFIA's First Light flight:
https://www.sofia.usra.edu/multimedia/science-results-archive/nasa%E2%80%99s-airborne-observatory-sees-%E2%80%9Cfirst-light%E2%80%9D-flight

SOFIA Science Case Study: M2-9 Planetary Nebula
How the Universe Makes Elements

Before reading, review the following key terms (Glossary, pages 8-11):
angular resolution, interstellar medium (ISM), nebula, nucleosynthesis, planetary nebula.

Background: Astronomers surveying the sky during the 18th and 19th centuries discovered dozens of small colorful **nebulas**. (Nebula is the Latin word for cloud.) Many of these nebulas are greenish-blue and circular in shape. The **planets** Uranus and Neptune that were discovered during the same period are also greenish-blue and circular. Moreover, those planets have about the same apparent sizes as the nebulas. Only a few days of observing is needed to tell a planet from a nebula. Planets move relative to the stars, nebulas do not. So, those small circular greenish-blue nebulas were nicknamed **planetary nebulas** because they were mistaken easily for planets by impatient planet hunters.

After decades of research, scientists now understand that planetary nebulas are clouds of material expelled by some stars during their final life stages. Photos of planetary nebulas made over long time spans show that they are expanding away from their respective central points. At the center of each planetary nebula lies a type of object called a **white dwarf**. White dwarfs are hotter than the Sun but also much smaller, denser, and less luminous. A white dwarf is understood to be the burned-out remnant of the original star.

The planetary nebula material expands, cools, and fades to become invisible. Finally, all that is left is the white dwarf "corpse". Based on observations and computer models, this type of stellar death seems to be limited to stars that are about the same mass as our Sun.

During a star's lifetime, nuclear reactions in its core transform hydrogen into heavier elements such as helium, carbon, and oxygen. The process of element formation is called **nucleosynthesis**. The material in the expanding planetary nebula contains some of the heavy elements produced by the star. Those elements eventually mix into the **interstellar medium (ISM)**.

Material expelled by a dying star thus can be "recycled" into the next generation of stars and planets that will form from the ISM. Astronomers want to improve their understanding of this recycling process.

The Target: Raghvendra Sahai and Michael Werner, astronomers at NASA's Jet Propulsion Laboratory, proposed to use **SOFIA** to observe a planetary nebula named M2-9. Its name prefix "M" refers to the fact that it is in a catalog of planetary nebulas compiled by astronomer Rudolph Minkowski.

M2-9 is especially interesting to scientists because it does not have the spherical shape of many other planetary nebulas. Dying stars at the centers of planetary nebulas often expel their outer material in symmetric "bubble" shapes. In contrast, M2-9 is nicknamed "The Butterfly" because it looks like it has two wings extending away from the center. Something unknown is causing the M2-9 nebula material to be expelled in just two directions. Raghvendra and Mike were curious about whether the material in the M2-9 nebula is similar to, or different from, material in other such nebulas. And, if M2-9’s material is different, they wondered whether that might be connected somehow to M2-9’s unusual shape.

Previous Research: Many astronomers have studied M2-9 at visual wavelengths using ground-based observatories. Raghvendra also observed this nebula several years earlier using the Hubble Space Telescope. Later, with Mike, Raghvendra studied M2-9 at **near-infrared** and **mid-infrared** wavelengths using the Spitzer Infrared Space Telescope.

Instrument selected: Raghvendra and Mike formed a team with colleagues from the U.S. and Europe plus the SOFIA scientific staff to make further studies of M2-9. They decided to use the FORCAST mid-infrared **imager** (Figure 1).

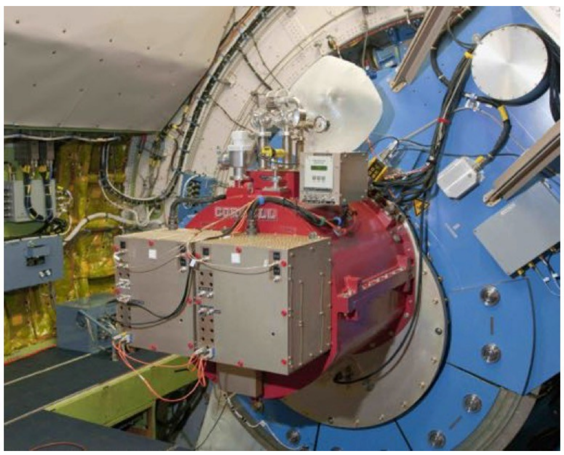


Figure 1: The FORCAST (Faint Object infRared Camera for the SOFIA Telescope) imager consists of the red cryostat (cold container) plus gold electronics boxes shown here mounted on SOFIA’s telescope.

Raghvendra and Mike had three important reasons why they chose SOFIA and FORCAST for the new M2-9 study. (1) Their Spitzer observations indicated that the dust grains in the M2-9 outflows have temperatures such that, according to **Wien’s law**, they would produce mostly mid-infrared radiation. Mid-infrared light is what the FORCAST imager detects. (2) Because SOFIA operates in the stratosphere, they could make observations at wavelengths longer than 25 **microns** that are impossible to observe with ground-based telescopes. (3) SOFIA’s telescope is three times the size of Spitzer’s telescope. Because of the effect of **diffraction**, SOFIA’s telescope would have three times better **angular resolution** than Spitzer’s telescope. Using SOFIA would thus allow them to see details three times smaller in M2-9. (Read SOFIA Science Overview section II.B for more information about telescopes and angular resolution.)

Results and Interpretation: Raghvendra and Mike flew on SOFIA twice, in May and June 2011, to make the observations of M2-9 they had proposed. They took images of M2-9 at wavelengths of 6.6, 11.1, 19.7, 24.2, 33.6, and 37.1 microns (Figure 2).

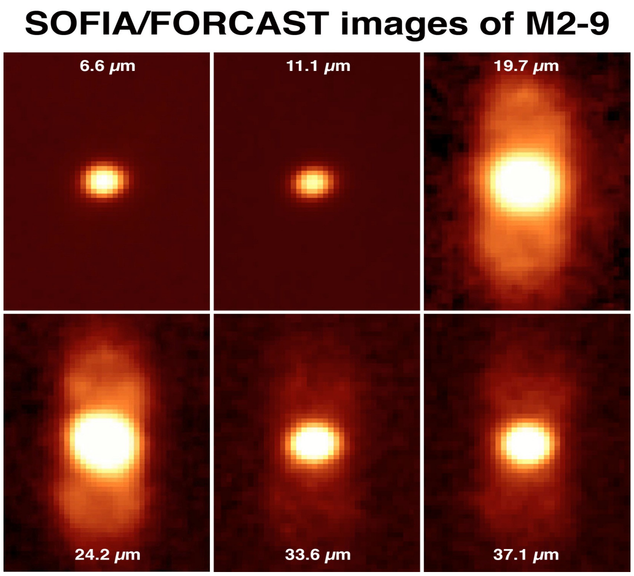


Figure 2: Images of planetary nebula M2-9 at six mid-infrared wavelengths. The central white dwarf star is the only thing seen in the 6.6 and 11.1 micron images because it is hotter than the dust in the nebula so, by Wien's law, its strongest output is at the shortest wavelengths. At wavelengths of 19.7 and 24.2 microns the light is mostly from dust in the outflow with temperatures around 100 K. At all of these wavelengths the effect of diffraction makes the small central white dwarf appear much larger than it actually is.

The team also had an image of M2-9 taken by the Hubble telescope at visual wavelengths (Figure 3, right) to compare with their infrared image (Figure 3, left). The bright areas in the visual-wavelength Hubble image show light from gas atoms. By comparison, the bright areas in the infrared image show light from solid dust grains. Those grains are condensing as the outflow gets farther from the central star and cools down. The scientists looked for features in one image that lined up with features in the other image. This would indicate regions of the nebula with concentrations of both gas *and* dust. Features that did not line up would indicate regions of the nebula where the gas and dust are separated.

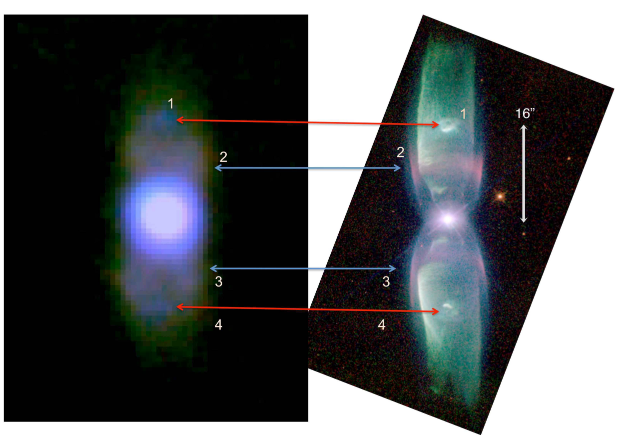


Figure 3: (Left) FORCAST composite mid-infrared image of M2-9. Representational colors: red = 19.7 microns, green = 24.2 microns, and blue = 37.1 microns. (Right) Hubble Space Telescope visual-wavelength image. Dust features in the infrared image are connected by numbered arrows with gas features in the visual image. Diffraction makes the central star appear much larger in the infrared SOFIA image than in the visual-wavelength Hubble image.

Raghvendra and Mike's team found clear correlations between dense knots of gas in the M2-9 outflow and locations where dust grains are concentrated (Figure 3). By comparing how much infrared light was produced by the dust at each wavelength, the team could use a mathematical model to estimate the sizes of the M2-9 dust grains. The scientists were surprised to find that grains in the M2-9 outflow seem to have a combination of two very different sizes: either about 0.1 micron, or bigger than 1 micron.

Usually, ISM grains are about 0.1 micron in size or smaller. Raghvendra and Mike's team expected to find typical ISM-sized grains in M2-9 nebula material flowing toward the ISM. The source of the larger-sized grains is a puzzle. The M2-9 team guessed that perhaps the large particles are not condensing in the outflow the way the small grains are. Instead, they hypothesized that the large grains were already present in a disk of material around the white dwarf star but got caught up and carried away by the outflow. The same disk might act as a barrier, forcing the outflow into just two directions to make the M2-9 "wings". If this hypothesis is right, it reveals the type of connection for which Raghvendra and Mike were looking, between the shape and composition of the M2-9 nebula.

Additional resource:

The original NASA news release regarding SOFIA's M2-9 observations: https://www.sofia.usra.edu/multimedia/science-results-archive/nasas-sofia-captures-images-planetary-nebula-m2-9

SOFIA Science Case Study: The Milky Way Galaxy's Circumnuclear Ring – *Dusty Ring Around a Black Hole*

Before reading, review the following key terms (Glossary, pages 8-11):
black hole, Circumnuclear Ring, Milky Way Galaxy, Sagittarius A* (Sgr A*).

Background: Until the early part of the 20th century, astronomers thought that our **galaxy**, the **Milky Way Galaxy,** is a disk of stars only a few thousand light-years across. They also thought that our **Solar System** is located near the Galactic center.

This view changed in the 1920s after astronomer Harlow Shapley measured the distances of star groups called **globular clusters**. Shapley discovered that these clusters are arranged in a swarm centered around a location tens of thousands of light-years from us. He concluded that this location is the center of our Galaxy (Figure 1). In other words, Shapley deduced that objects he could see (globular clusters) are arranged around a point that he could not see (the Galactic center). This is like seeing a group of vultures flying in circles far away, and deducing the location of their food without actually seeing the food itself.

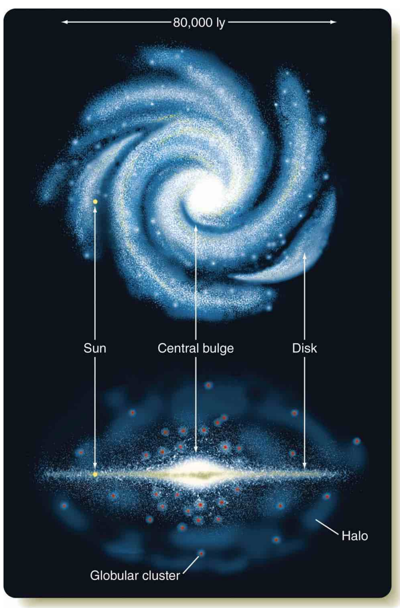


Figure 1: Artist's conceptions of the Milky Way Galaxy as if seen from outside: Face-on (top) and edge-on (bottom). Our Solar System, including the Sun and Earth, is located in the thin galactic disk about 27,000 light-years from the Galactic center. The globular star clusters studied by Shapley, each containing hundreds of thousands of stars, are located in a spherical halo around the disk, concentrated toward the center. (Adapted from *Foundations*, Seeds & Backman, © 2016 Cengage.)

When astronomers look at visual wavelengths toward the region of space that Shapley identified as the Galactic center they see nothing remarkable. That is because dust in the **interstellar medium** lying in the plane of the Galaxy blocks light. To overcome this problem, astronomer Eric Becklin used a **near-infrared** detector to map the Galactic center. Infrared light penetrates interstellar dust more easily than can visible light, and ordinary stars produce substantial amounts of near-infrared light. Eric's near-infrared detector could "see" through the dust, allowing him to measure where the density of stars is greatest. This was a determination of the Galactic center's precise location, right about where Shapley predicted it should be. (Read SOFIA Science Overview section II.D regarding the types of object best studied at infrared wavelengths.)

In the 1970s, astronomers found an unusual source of radio radiation at the Galactic center position determined by Becklin. They dubbed this radio source **Sagittarius A*** (**Sgr A*** for short, pronounced Sadge-A-star). "Sagittarius" means it is in the direction of the constellation Sagittarius. The brightest radio source in each constellation is designated as "A". Finally, "*" means that it is an unresolved point, like a star. Astronomers have evidence that Sgr A* is a supermassive **black hole.** The radio radiation is hypothesized to be coming from an **accretion disk**, a disk of compressed, hot material swirling right around the black hole.

Previous Research: A few years after his discovery of the Galactic center, Eric Becklin and other astronomers used the **Kuiper Airborne Observatory (KAO)** to make a **far-infrared** map of the region around Sgr A*. They found a ring of gas and dust about 5 light-years in radius they dubbed the **Circumnuclear Ring** (**CNR)**. The CNR is sometimes known as "the Ring" for short.

Later, the Hubble Space Telescope made a near-infrared image of this region (Figure 2). That image indicates that the Galactic center contains millions of stars plus clouds of gas and dust dense enough to block the light from background stars. Those blocking clouds are seen as blank spots in Figure 2.

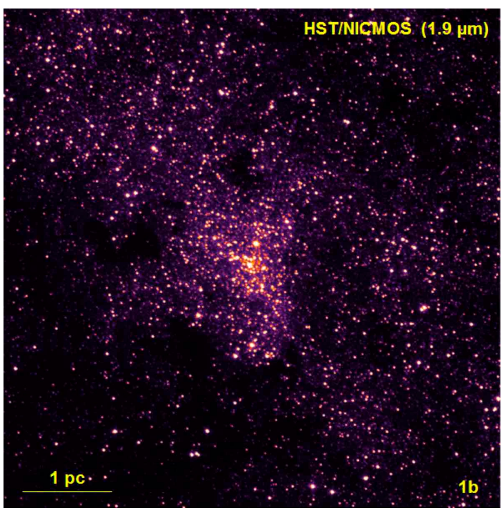


Figure 2: Hubble Space Telescope near-infrared (wavelength = 1.9 **microns**) image of the Milky Way Galaxy's central region. The scale bar shows a span of 1 pc (parsec; 3.3 light years). The entire frame is about 26 light-years across. At this wavelength we see mostly the light coming from millions of stars in the Galaxy's central cluster.

The Target: Ryan Lau and his Cornell University doctoral professor Terry Herter wanted to study the Galactic center using **SOFIA**. Terry and his collaborators had been awarded some guaranteed SOFIA observing time to study objects of their choosing because Terry led the team that designed and built the FORCAST **imager**. They decided to use some of that guaranteed time to make an improved map of the Ring to better determine its properties. That information could then be used to better understand how the Ring formed and how it is evolving.

Instrument Selected: Ryan, Terry, and their teammates planned to use SOFIA and the FORCAST **mid-infrared** imager (Figure 3) for their observations of the Ring. Earlier observations from the KAO indicated that the Ring has strong emission at wavelengths detected by FORCAST. Also, the FORCAST field of view is well-matched to the size of the Ring.

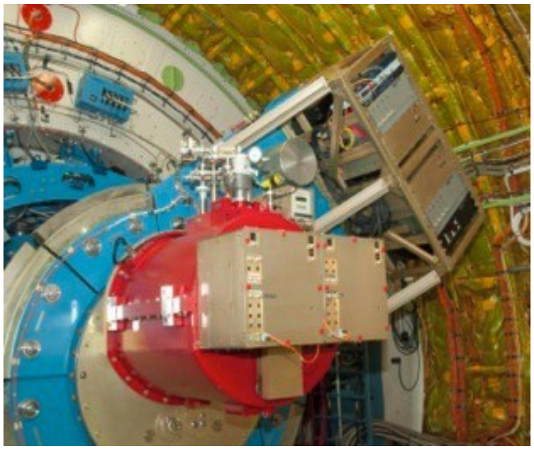


Figure 3: The FORCAST (Faint Object infRared Camera for the SOFIA Telescope) imager consists of the red cryostat (cold container) plus gold electronics boxes shown here mounted on SOFIA's telescope

Results and Interpretation: In June 2011, Ryan, Terry, and other scientists on their team flew onboard SOFIA to observe the Galaxy's Circumnuclear Ring. Ryan's team took images of the Ring at wavelengths of 20, 32, and 37 microns. Ryan chose a **representational color** scheme of blue = 20 microns, green = 32 microns, and red = 37 microns to represent the Ring's infrared light. Then, he combined the three 1-wavelength component images into a final composite image (Figure 4).

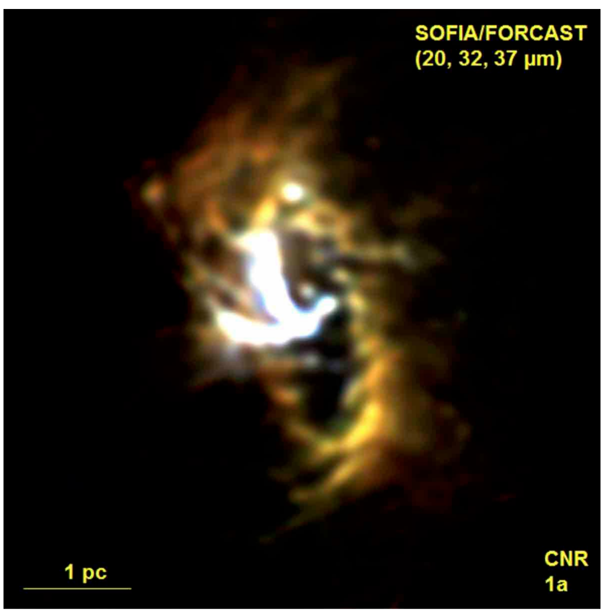


Figure 4: Composite SOFIA / FORCAST mid-infrared image of the Galactic center with the same field of view as Figure 2. The Circumnuclear Ring (CNR) is prominent at mid-infrared wavelengths, but light from stars is relatively negligible.

First, Ryan's team compared their mid-infrared image of the Galactic center with the Hubble Space Telescope image of the same region (Figure 2). The SOFIA / FORCAST image clearly shows the Circumnuclear Ring. The blank spots in the Hubble image are areas where the Ring is most dense and blocks the light from background stars. The white feature in the interior of the ring that looks like a bird in flight is actually three "arms" of gas. Those arms extend from the inner edge of the Ring to its center. Sgr A* itself is located where the three arms intersect. The arms have a representational color of white because their material radiates strongly at all three wavelengths observed.

For the next step in the analysis, Ryan produced a temperature map of the Ring (Figure 5). The temperatures were determined using **Wien's law** regarding the relationship between an object's temperature and its wavelength of strongest output. (Read SOFIA Science Overview section I.C for more information about Wien's law.)

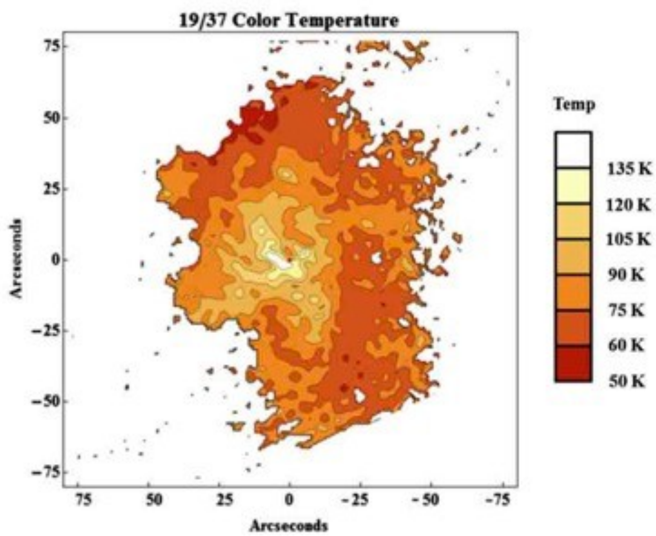


Figure 5: Map of temperatures in the Ring based on the ratio at each location of the brightness at wavelengths of 19 and 37 microns. This temperature map has the same field of view as Figures 2 and 3. Note that the highest temperatures are at the Ring center and in the "arms" visible in Figure 4. That is the region of the crowded central star cluster seen in Figure 2.

Temperatures in the Ring range from 50 to 85 **Kelvin**, with the highest temperatures (areas colored light yellow) found in the inner edge of the ring plus the three "arms". The lowest temperatures (colored deep orange) are at the outer edge of the Ring. Ryan's team interpreted this to mean that the Ring is heated by a radiation source near the Ring's center. Scientists had previously hypothesized that the Ring could be heated by the millions of stars in the cluster's center, or by radiation from the Sgr A* accretion disk. (Note: The accretion disk is not the CNR. The black hole's accretion disk is much too small to see in these images.) Ryan calculated that the millions of stars in the center of the Ring would be more effective at heating the Ring than the weaker radiation from the accretion disk.

Ryan and his team also carefully examined the shape of the Ring. They concluded that it is circular and tilted relative to our line of sight; the tilt is what makes the Ring appear elliptical. This agrees with previous models made by other scientists that were based on measurements of motions of gas in the Ring.

Additional resource:

The original NASA news release regarding SOFIA's Circumnuclear Ring observations:
https://www.sofia.usra.edu/multimedia/science-results-archive/sofia-spots-recent-starbursts-milky-way-galaxys-center

SOFIA Science Case Study: Water in Sunlit Lunar Soil
Secrets Hidden in Moonlight

Before reading, review the following key terms (Glossary, pages 7-10):
Mare, volatile, spectrum/spectra, pectral line, micron, spectrometer, grism, pixel, peer review

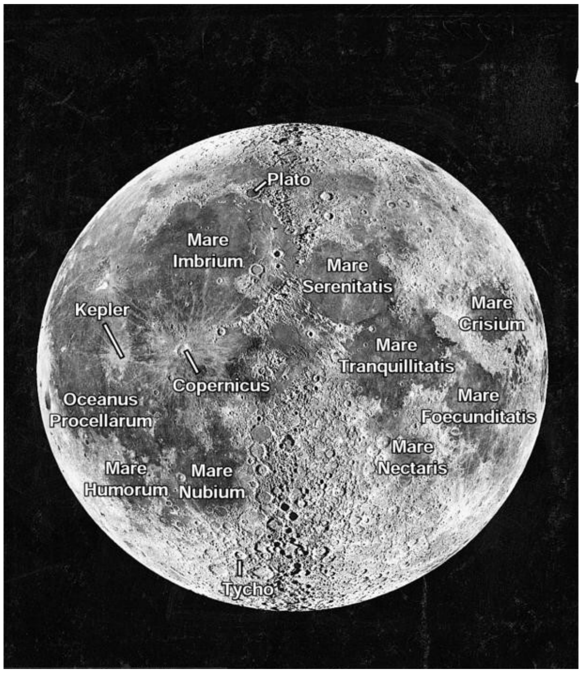


Figure 1: Image of the Moon with labeled surface features.(From *Foundations*, Seeds & Backman © 2016 Cengage Learning)

Background: Above is a photo of the full moon with labels added for some surface features. The first astronomers using telescopes thought the large dark features were bodies of water and gave them aquatic names such as the Sea of Tranquility. In Latin, that's Mare Tranquillitatis (pronounced *mah-ray tran-kwill-ih-tah-tiss*), at center-right in the image. ("**Mare**" means "sea".) Those "seas" are actually smooth plains made by lava that flowed across the Moon's surface and solidified long ago. The Sea of Tranquility was the landing site for NASA's Apollo 11 in 1969, the first human landing on the Moon.

Previous Research: A big surprise for planetary scientists came from detailed analyses of the lunar rock samples brought back by the Apollo astronauts. Those rocks are quite similar in composition to Earth's crust and mantle. But, at one time that material had been heated to a high enough temperature that most of the **volatile** substances, including water, were removed. The lunar "seas" are actually remarkably dry.

In the late 1990s the orbiting spacecraft Lunar Prospector detected large amounts of hydrogen at the Moon's poles. To find out whether that hydrogen is in water (H_2O), NASA developed the Lunar Crater Observation and Sensing Satellite, LCROSS (pronounced *el-cross*). LCROSS had two parts. One part was a projectile that slammed into the lunar surface and kicked up a cloud of dirt and rock fragments. The other part was an instrumented spacecraft that flew hrough the cloud and measured its composition. LCROSS was aimed at a crater near the Moon's south pole. The permanently shadowed, extremely cold floor of that crater was hypothesized to have trapped water ice in the soil. The LCROSS data confirmed that some of the hydrogen at the lunar poles is in crystals of water ice.

When light from an object is spread into its component colors, called a **spectrum (**plural: **spectra),** narrow features can be seen in the spectrum that are called **spectral lines**. Spectral lines are identifying "fingerprints" of different atoms and molecules. Figure 2 shows an example of a spectrum of water vapor. The spectrum is in the form of a plot of light intensity (vertical scale) as a function of wavelength (horizontal scale). The decreases in intensity ("dips") at wavelengths around 3-4 **microns** and 6 microns are two absorption spectral lines of water vapor. Note that spectral lines of water in solid, liquid, and vapor form will not necessarily be at exactly the same wavelengths. Also note that, depending on the temperature of the material and the wavelength of the specific spectral line, a spectrum can show emission lines that appear as increases instead of decreases in intensity relative to the rest of the spectrum.

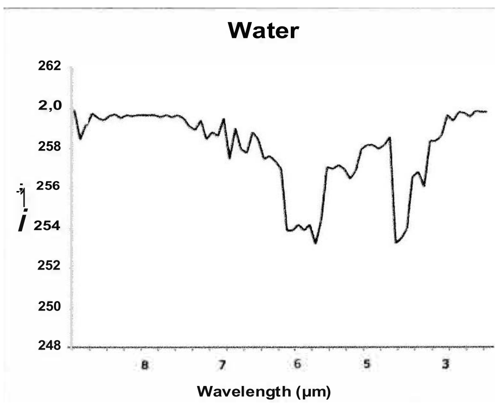


Figure 2: Absoprtion spectrum of water vapor. (Adapted from *Project SPECTRA!: Goldilocks and the Three Planets*, U. Colorado LASP.)

Other spacecraft before and after LCROSS detected a broad spectral line in sunlight reflected from the lunar surface at wavelengths around 3 microns. That spectral line was caused by some unidentified hydrogen-bearing molecule. Importantly, it was found in sunlit regions, far away from the poles. But, measurements at only the 3 micron wavelength can't determine whether the hydrogen is in hydroxyl (OH) or water (H_2O) molecules.

The Target: University of Hawai`i Ph.D. student Casey Honniball and her advisor Paul Lucey knew that finding a 6 micron spectral line in addition to the 3 micron line would distinguish between OH and H_2O in lunar soil. They also knew that 6 micron radiation from celestial objects is not detectable from the ground nor from existing spacecraft. But, they knew that by using SOFIA**,** flying above water vapor in Earth's atmosphere, they could take 6 micron spectra.

Casey and Paul assembled a team including collaborators from the University of Colorado, Georgia Institute of Technology, Johns Hopkins University, and NASA. They requested and were granted observing time on SOFIA to check whether the Moon has water-bearing soil away from the poles.

Casey and her collaborators chose to focus on the region around the large crater Clavius that they expected would be easy to spot in SOFIA's guider cameras. They also observed comparison locations near Mare Serenitatis (pronounced *mah-ray seh-ren-ih-tah-tiss*; "Sea of Serenity") where Apollo astronauts gathered rock samples that were found to be very dry (Figure 3).

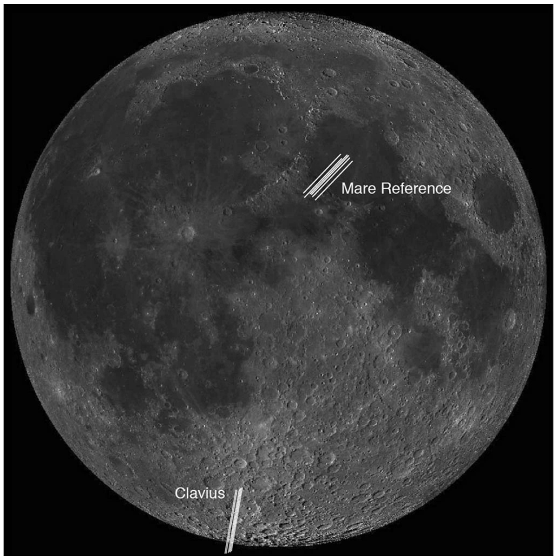
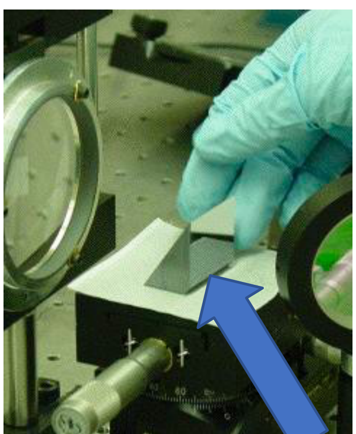


Figure 3: Clavius crater and Mare "Reference" (Mare Serenitatis) regions observed by SOFIA indicated on a Lunar Reconnaisance Orbiter spacecraft image. (Honniball et al. 2021, *Nature Astronomy 5*, 121, Extended Data Figure 1; used with permission.)

Instrument Selected: The FORCAST **imager** operates at mid-infrared wavelengths. The FORCAST wavelength range includes 6 microns, appropriate for the lunar water study. So, this was the instrument Casey and her collaborators chose for their project. (Read SOFIA Science Overview section II.E for more information about SOFIA's instruments.)

The team requested use of a **grism** (grating plus prism; Figures 4 & 5) to convert FORCAST into a **spectrometer** capable of measuring spectra.



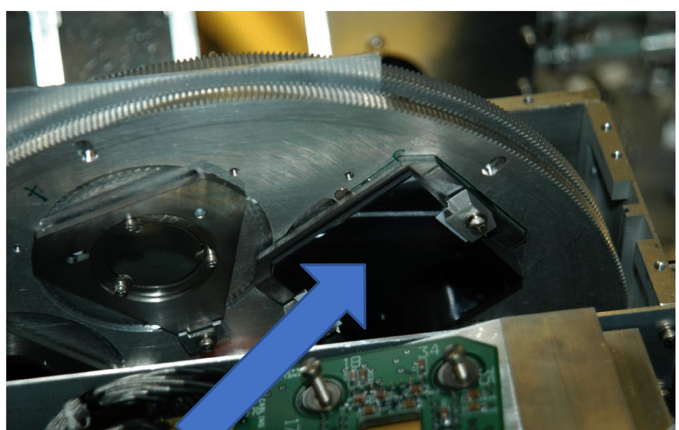


Figure 4: 4-8 micron grism. **Figure 5**: Grism in the FORCAST filter wheel. (Ennico et al. 2006, Proc. of SPIE Vol. 6269 1Q, Figures 8a & 9; used with permission.)

A grism is installed in the instrument's filter wheel (Figure 5). The filter wheel is controlled by software run by the instrument operator. The grism can be put in the path of the light gathered by the telescope and sent through the instrument to the detector. The result is that the light is spread into an array of spectra, one for each **pixel** in the image. In each exposure FORCAST gathered light from a rectangular slit covering part of the Moon up to 4.5 x 360 kilometers (2.8 x 220 miles) in size.

You might think that observations of the Moon would be super easy, but that's not the case. The Moon continuously moves in its orbit around the Earth. To stay on target the telescope has to track at a different rate than the rate used to observe stars and galaxies. Of course, this is especially difficult for SOFIA's telescope that is also contantly moving. Also, the Moon is much brighter than the usual targets of SOFIA observations. Filters had to be put in front of the tracking cameras to partly block the light (Figure 6).

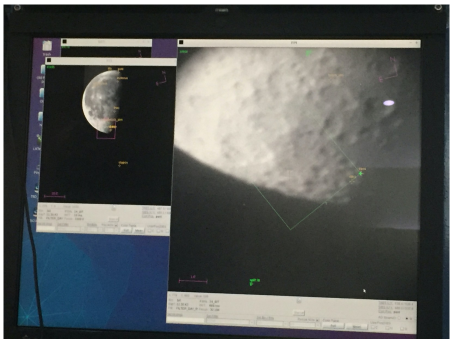


Figure 6: The Moon as seen by the SOFIA telescope guider cameras with light blocking filters, viewed at the educators console. (NASA / SOFIA / SETI Institute)

Results and Interpretation: The first lunar spectra were taken by Casey and her team in 2018. They took the data back to their home institutions for more careful analysis. The 6-micron lunar water signal near Clavius crater turned out to be quite strong. Their early results were so impressive that SOFIA observatory director Margaret Meixner gave them extra time to make confirming observations in 2019.

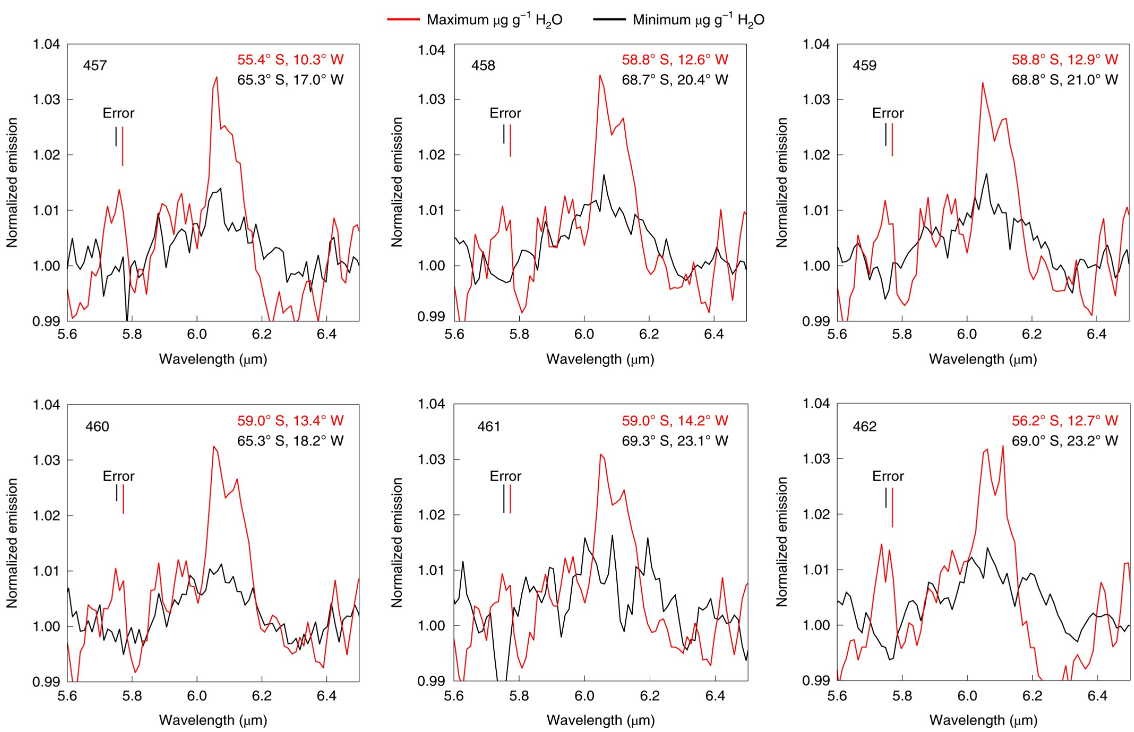


Figure 7: Twelve mid-infrared spectra of the Moon's surface near Clavius crater. (Honniball *et al*. 2021, *Nature Astronomy* 5, 121, Figure 1; used with permission.)

Figure 7 shows the fully analyzed data. Each panel shows two spectra from one of the six rectangular slit regions observed on the Moon's surface near Clavius. The spectra displayed as red curves are from locations within the slit with relatively high water abundances. Those spectra have emission peaks (strong signals) at wavelengths around 6 microns. The spectra displayed as black curves are from nearby locations with lower, but not zero, water abundances, shown by lower peaks around 6 microns. The location on the Moon of each spectrum is given by the lunar latitude and longitude values in the upper right corner of each panel. The relative amounts of uncertainty in the spectra are indicated by the sizes of the error bars at upper left in each panel.

The strength of the water signal varied widely among the twelve locations sampled near Clavius (Figure 7). Casey and her team calculated that the amount of water ranged between 100 to 400 micrograms per gram of soil. The average amount equals a 12-ounce water bottle's worth in each cubic meter of lunar dirt. In contrast, comparison locations observed near Mare Serenitatis had significantly less water. The research team speculated that the water must be trapped in soil grains or glass beads (particles of melted and re-solidified soil) so it isn't evaporated by the harsh lunar sunlight.

Casey and her collaborators wrote up their results in a scientific paper, "Molecular water detected on the sunlit Moon by SOFIA"**,** that they submitted to the journal *Nature Astronomy*. Their paper was anonymously critiqued by scientists who are experts in related fields. That process is called **peer review**; it is a normal part of the publication of any scientific paper. The lunar water paper was accepted for publication in October 2020, at which time NASA produced a news release about these exciting results.

Casey received her Ph.D. from the University of Hawai`i and moved to a post-doctoral position at NASA's Goddard Space Flight Center in Maryland. She continues to lead her team in making more SOFIA lunar water observations at more locations in the lunar landscape.

The LCROSS and SOFIA detections of water in a shadowed lunar crater and in sunlit lunar soil caused a real change in thinking about the Moon. There is water in the lunar soil, perhaps enough to support a human lunar colony. That H_2O would provide the colonists not only drinking water but is a potential source of fuel and oxygen. These precious supplies could be harvested from the soil on the Moon instead of hauling from Earth all that humans colonists would need.

Additional resources:

The original NASA & SOFIA news releases regarding the SOFIA lunar water detection:
https://www.nasa.gov/press-release/nasa-s-sofia-discovers-water-on-sunlit-surface-of-moon
https://www.sofia.usra.edu/multimedia/science-results-archive/sofia-detects-water-moon

Honniball *et al*. technical journal article: https://doi.org/10.1038/s41550-020-01222-x

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