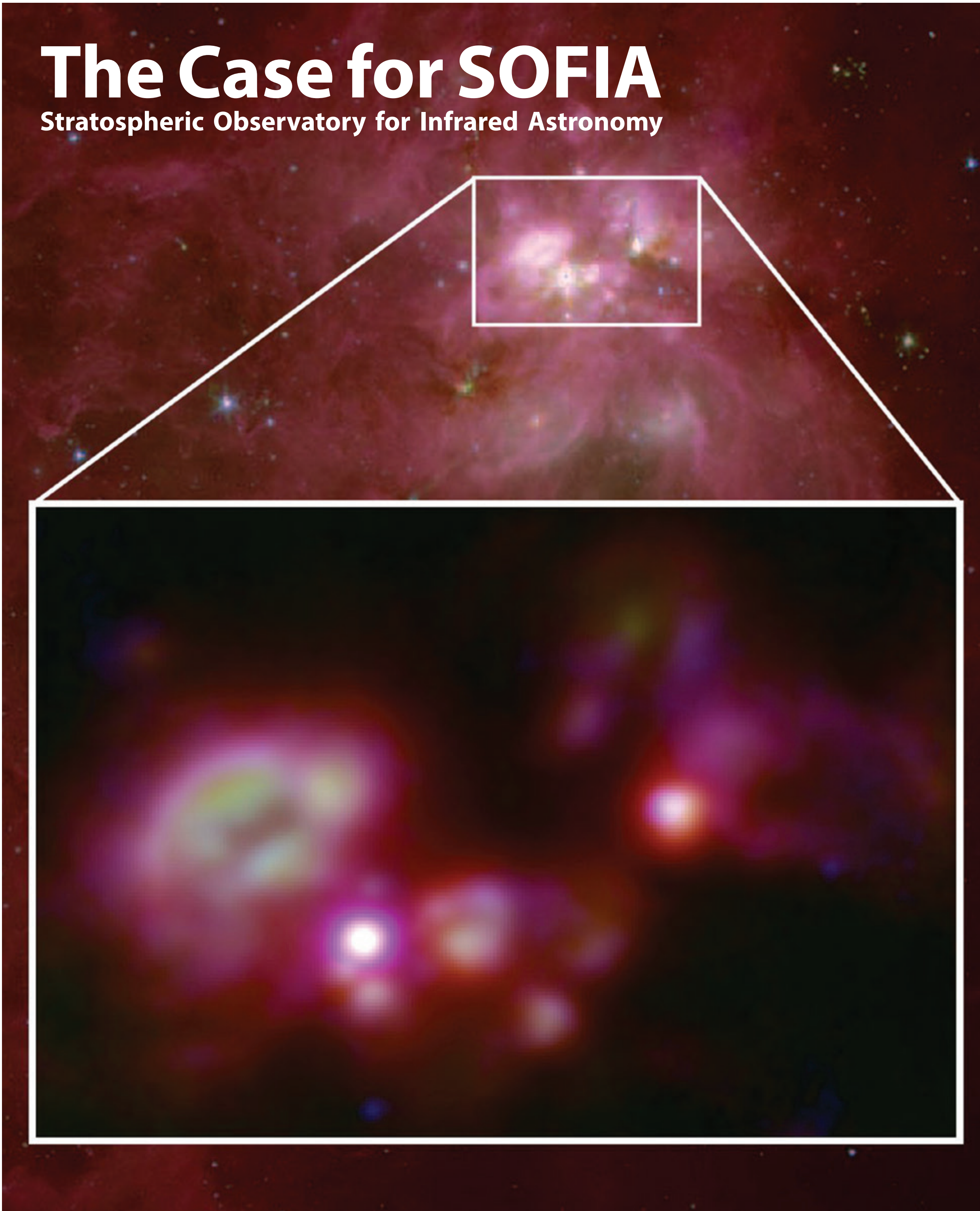
The Case for SOFIA

Stratospheric Observatory for Infrared Astronomy



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Welcome

Each generation leaves behind unfinished work for the young minds they inspired and trained. In general, astronomers straddle the past and future, testing their protégés on complexities that eluded their mentors. SOFIA bridges both worlds, connecting today's research leaders with tomorrow's pioneers unlike any other observing platform. An incubator for new science and new scientists — and a public ambassador for astronomy — SOFIA is the world's largest flying observatory.

SOFIA's vision, from Earth's sibling planets to faraway galaxies, enables discoveries by guest investigators from around the world. SOFIA is poised for service, providing a platform for collaboration, technology innovation, and scientific discovery to address the epic questions that drive NASA's space science program.

This overview is designed to provide a broad-brush rationale for the case for SOFIA, designed for an interested non-technical audience. More detailed information can be obtained from a companion "SOFIA Science Vision" document and from our website: www.sofia.usra.edu.

Figure 1. SOFIA flying over the Sierra Nevada mountains during an early test flight. The telescope door is open, though the mirror is under a protective cover. This image was taken by a NASA F-18 chase plane. In operations, SOFIA flies at night and provides otherwise unobtainable views of the universe at infrared wavelengths. (NASA/Jim Ross)

SOFIA Overview

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a powerful new ship in NASA's research fleet. As the largest flying astronomical observatory in the world, SOFIA enables both scientific discovery and public engagement. SOFIA's potential is so compelling that the German Space Agency (DLR) has joined into a partnership with NASA to fund 20 percent of SOFIA's development and operations cost, and the international collaboration this partnership promises unites science as well as scientists.

Aboard SOFIA astronomers can conduct comprehensive investigations of diverse cosmic environments, collecting data for understanding all parts of the great story of the evolution of the Universe. Educators, young scientists-in-training, and journalists also fly on SOFIA, making it a valuable ambassador to the public and training platform at a time when our continued national and economic security calls for improvements in scientific literacy.

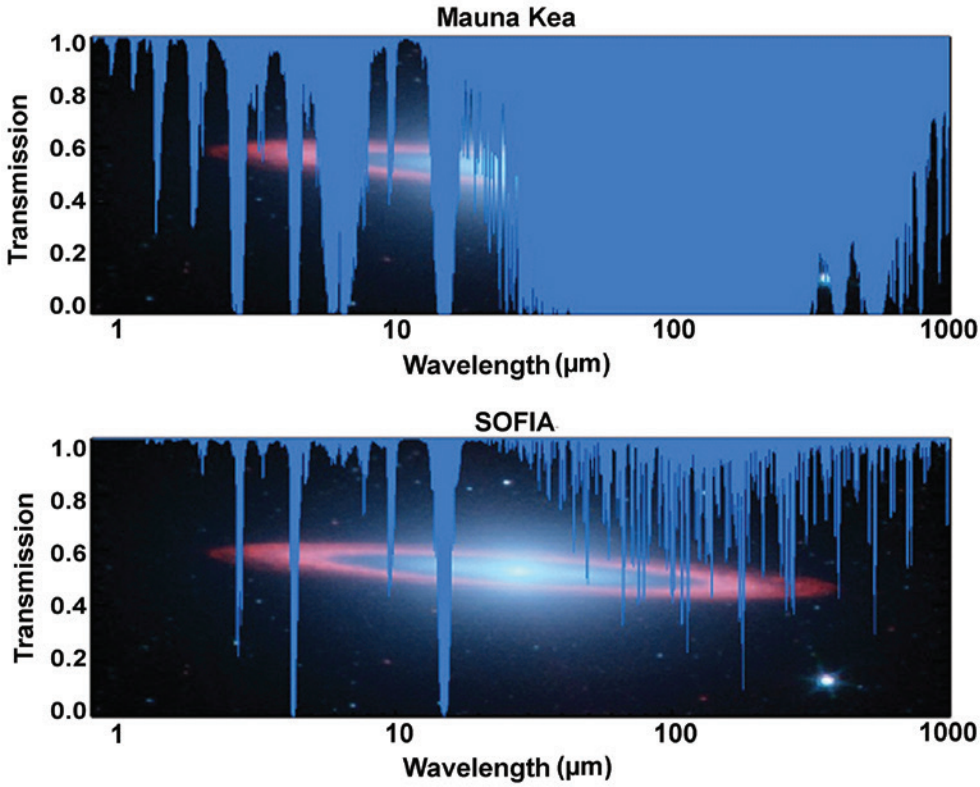


Figure 2. Typical atmospheric transparency at an altitude of 45,000 feet as compared with the transparency at the summit of Mauna Kea, an altitude of 13,800 ft. Blue strips extending all the way from the top to bottom of the panels indicate wavelengths of light blocked by Earth's atmosphere. The difference between the lower and upper panels is striking: at SOFIA's operating altitude, the atmosphere above the observatory is nearly transparent across this entire wavelength range, with the exception of two narrow blocked bands. **SOFIA enables observations that are impossible even from observatories on high mountain peaks.** Background: False-color infrared image of the Sombrero Galaxy (NASA/JPL-Caltech/Spitzer).

SOFIA consists of a German-built telescope with an effective diameter of 2.5 meters, embedded in a modified Boeing 747SP aircraft supplied by NASA (Figure 1). Observing while flying at altitudes up to 45,000 feet (14 km), the observatory gets above more than 99 percent of the atmospheric water vapor and other infrared-absorbing gases, thereby opening windows to the universe not available from the ground (Figure 2). SOFIA will usefully detect astronomical objects within a huge range of wavelengths between 0.3 and 1600 microns. For comparison, the human eye is only sensitive to light with wavelengths between 0.4 and 0.7 microns.

Built to fly for two decades, in full operations SOFIA will offer international science teams approximately 1,000 cloud-free high-altitude science observing hours per year. Observers are selected through a rigorous peer review process. Compelling discoveries will inspire the development of future technology — technology that can be readily demonstrated in new instruments on SOFIA.

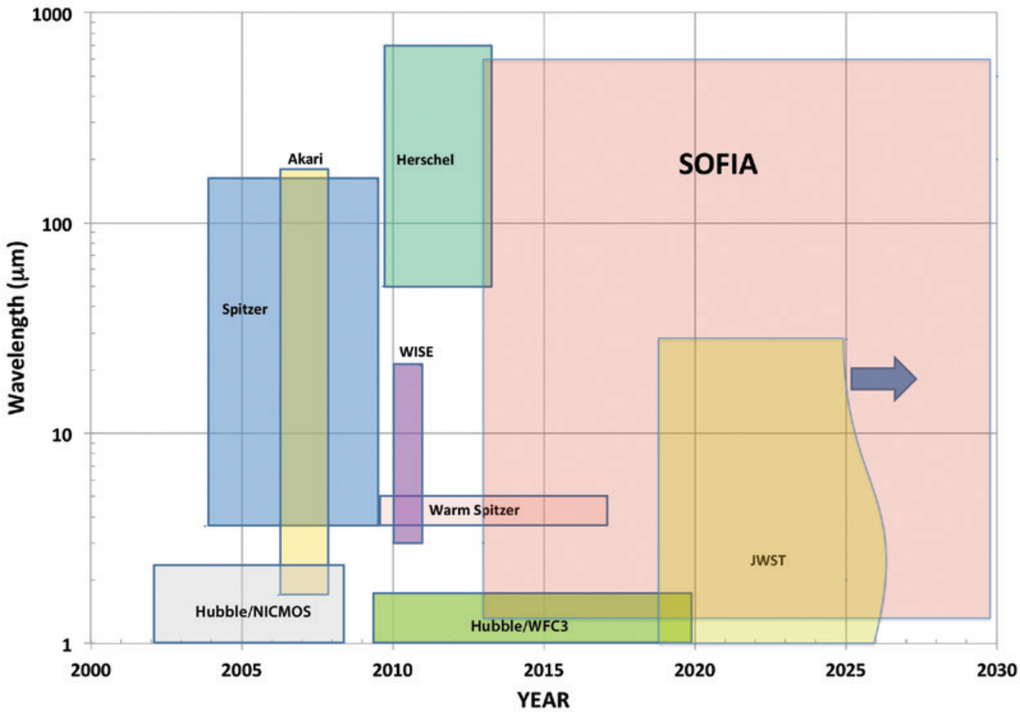


Figure 3. Capabilities and operating time spans of modern infrared space-based observatories (recently decommissioned, still active, and/or currently in development) compared with SOFIA. Potentially comparable proposed missions such as SPICA are not displayed because they have not entered formal development phases. **SOFIA covers both a wide wavelength range and operating lifetime, providing a platform for observations and discoveries not possible with other facilities.**

Science: With unique capabilities, and as a complement to peer missions, SOFIA deepens the grand narrative of how matter organizes itself into celestial bodies through four cosmic environments: Galaxies and the Galactic Center, the Interstellar Medium, the Formation of Stars and Planets, and the Solar System.

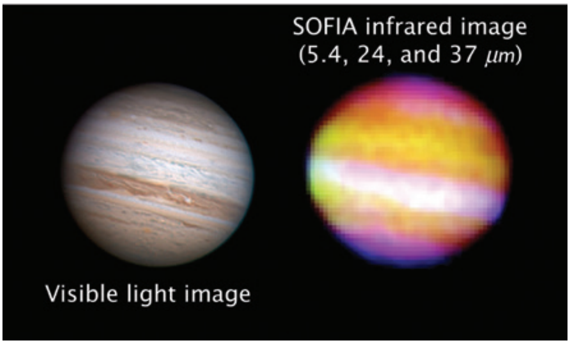
Scientific Instruments: Upon lift-off, spacecraft carry outdated technology, due to the long lead times from selection to launch. The first generation of seven SOFIA science instruments covers wavelengths ranging from the visible into the microwave, with a mixture of cameras and high-resolution spectrometers. However, this is only the beginning. The case for SOFIA rests firmly on the ability to replace or improve on the instrumentation designed today, so that science can meet the future. The observatory is a platform for innovation. Instrumentation can evolve with improvements in sensitivity, detector response time, observation technique, spectral resolution, and more. For precedent, one need look only at how upgrades to the Hubble Space Telescope have enhanced its productivity, expanding capability tremendously with each upgrade delivered. The next generation of infrared instrumentalists can be trained by developing and deploying improved technology. The number of students touched by SOFIA over the course of its lifetime will be in the thousands.

Figure 4. From left, Terry Herter, principal investigator of the FORCAST camera and SOFIA staff scientist James De Buizer discuss an infrared image with Airborne Astronomy Ambassadors Theresa Paulsen and Marita Beard. (NASA/SOFIA/ASP/N. Veronico)

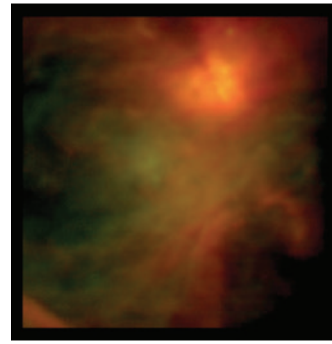
Education: SOFIA is the only major astronomical research observatory designed from the start to bring non-scientists into close contact with scientists in a research environment. SOFIA will serve varied audiences, for the citizen-scientist and scientist-citizen. A citizenry trained in evidence-based inquiry is well suited to thrive in a democracy.

Teachers and other educators fly on SOFIA so they can take their training, experiences, and inspiration back to the nation's classrooms and science museums. The SOFIA outreach program also prepares educational material for grades K–14, in physics, astronomy, and astrobiology.

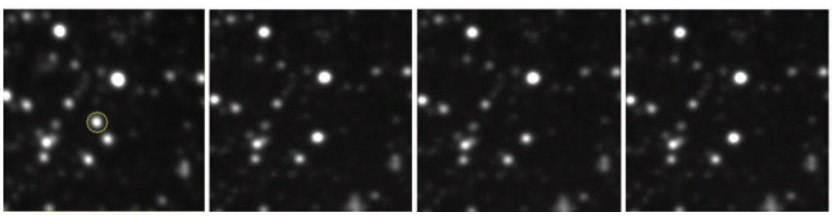
Selected SOFIA Science Results



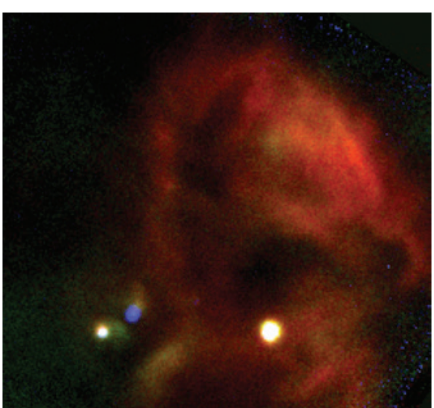
May 26, 2010: FORCAST mid-IR image of Jupiter from SOFIA's First Light flight compared with a visual-wavelength image of approximately the same face of the planet. The white band in the infrared image shows heat pouring out of the interior of Jupiter that was trapped when the planet formed 4.5 billion years ago. (Visual image: Anthony Wesley)



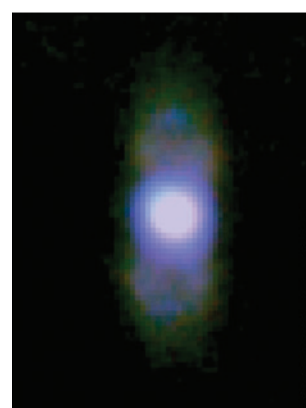
December 1, 2010: SOFIA/FORCAST mid-IR (19 & 37 microns) image mosaic of the M42 star-formation complex's core. This image shows the distribution of interstellar gas and dust clouds that are the raw material for the formation of new stars and planets.



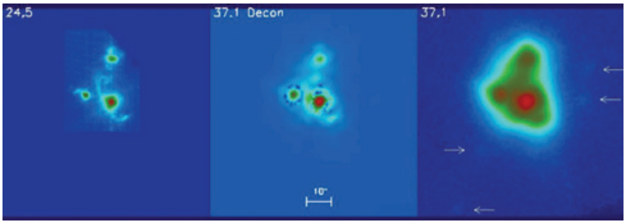
June 23, 2011: Pluto occultation image sequence from the optical Fast Diagnostic Camera (FDC) on SOFIA. Detailed measurements of the way Pluto blocked light from the background star allow determination of the structure of its atmosphere. (Courtesy Jürgen Wolf, Deutsches SOFIA Institut).



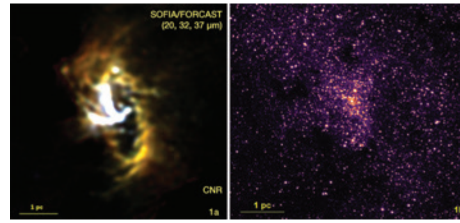
November 21, 2011: SOFIA/FORCAST mid-IR (5.4, 24, & 35 microns) image of the W40 star-forming region. These data allow analysis of the different stages of star formation at various locations in the cloud.



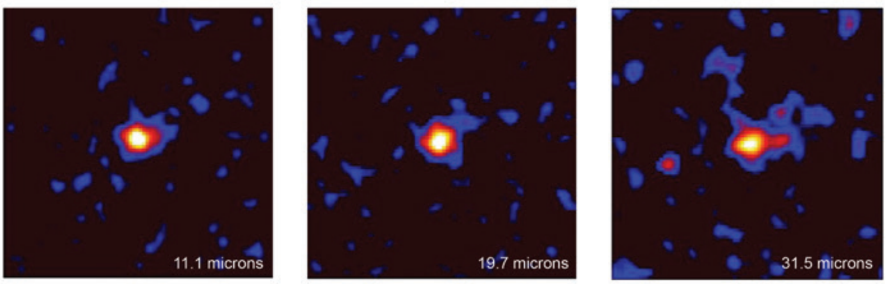
March 29, 2012: SOFIA/FORCAST mid-IR (20, 24, & 37 microns) image of planetary nebula M2-9. This nebula is material expelled by a star about the same mass as our Sun at the end of its life.



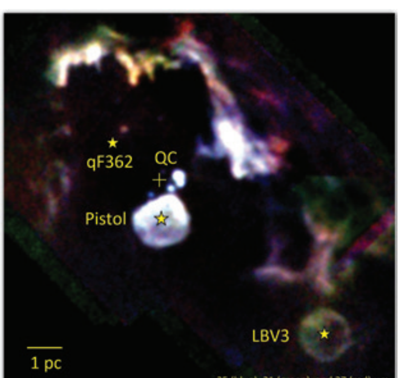
August 16, 2012: (left) Image of the S140 core at 24 microns from the Subaru telescope on Mauna Kea. (middle) Super-resolved SOFIA/FORCAST image at 37 microns. (right) Observed SOFIA/FORCAST 37 micron image before super-resolution processing. These data were partly a test of SOFIA's ability to resolve crowded clusters of bright infrared objects such as newborn stars.



January 8, 2013: SOFIA/FORCAST mid-IR (20, 32, & 37 microns) image of the Milky Way Galaxy's nucleus compared with an HST/NICMOS near-IR image of the same field of view. In the Hubble image, only stars in the Galaxy's nucleus can be seen. The SOFIA image reveals a ring of gas and dust revolving around the Galaxy's central supermassive black hole, with hot (white) streams of gas flowing down the drain.



October 24, 2013: SOFIA/FORCAST mid-IR (11, 20, & 32 microns) images of Comet ISON. The comet was observed by an array of ground-based and space observatories; SOFIA supplied a crucial measurement of Comet ISON's strongest emission which occurs at a wavelength inaccessible to any other observatory.



January 9, 2014: SOFIA/FORCAST observations of the Pistol and LBV3 Nebulae near massive stellar clusters at the Galactic Center. These nebulae are lit by some of the most luminous stars in the Galaxy that have formed by a process that differs from the process by which stars form in the Sun's neighborhood.

February 2014: Near-infrared images of galaxy M82 before (left, 2MASS) and during (right, SOFIA/FLITECAM) the explosion of Supernova 2014J. This type of supernova is used to calibrate measurements of cosmological distances and the Universe's expansion rate.

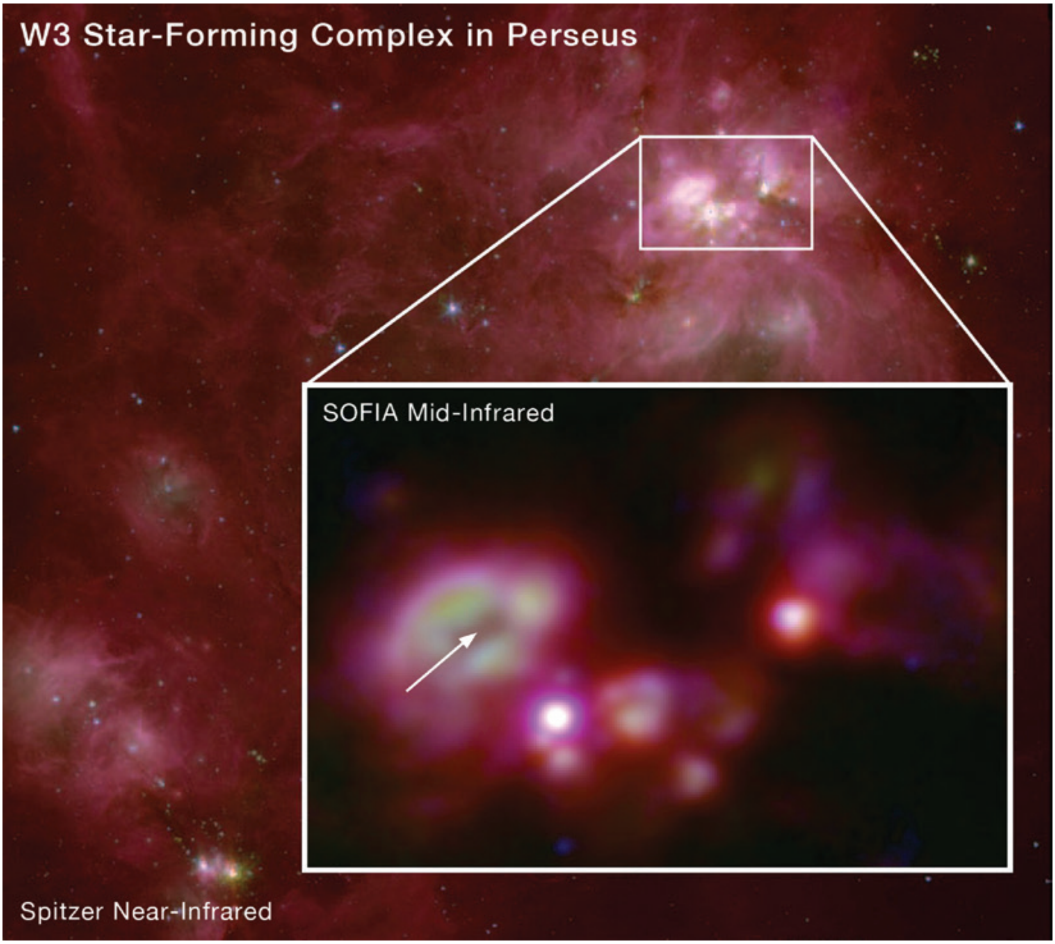


Figure 5. Mid-infrared image of the W3 star forming region from SOFIA/FORCAST, inset on a near-infrared image from Spitzer. The SOFIA image dimensions are 150 x 100 arcseconds, corresponding to 15 x 10 light years at a distance of 6400 light years. Arrow indicates a bubble cleared in the nebula by wind and radiation from the most massive newborn star in the cluster. SOFIA image, inset: Red, Green, Blue = 37, 20, 7.7 microns; NASA / DLR / USRA / DSI / FORCAST team / F. Salgado, A. Tielens, J. De Buizer. Spitzer image, background: Red, Green, Blue = 7.9, 4.5, 3.6 microns; NASA/JPL-Caltech.

Science Highlights

SOFIA successfully completed early science in the winter of 2011, using three scientific instruments: a mid-infrared camera (FORCAST), far-infrared spectrometer (GREAT), and high-speed optical photometer (HIPO). As of March 2014 we have celebrated the 150th flight and counting, including commissioning a near-infrared camera (FLITECAM), and the far-infrared imaging spectrometer (FIFI-LS). Early scientific results were published in special issues of *The Astrophysical Journal Letters* (v. 749, April 2012) and *Astronomy & Astrophysics* (v. 542, May 2012).

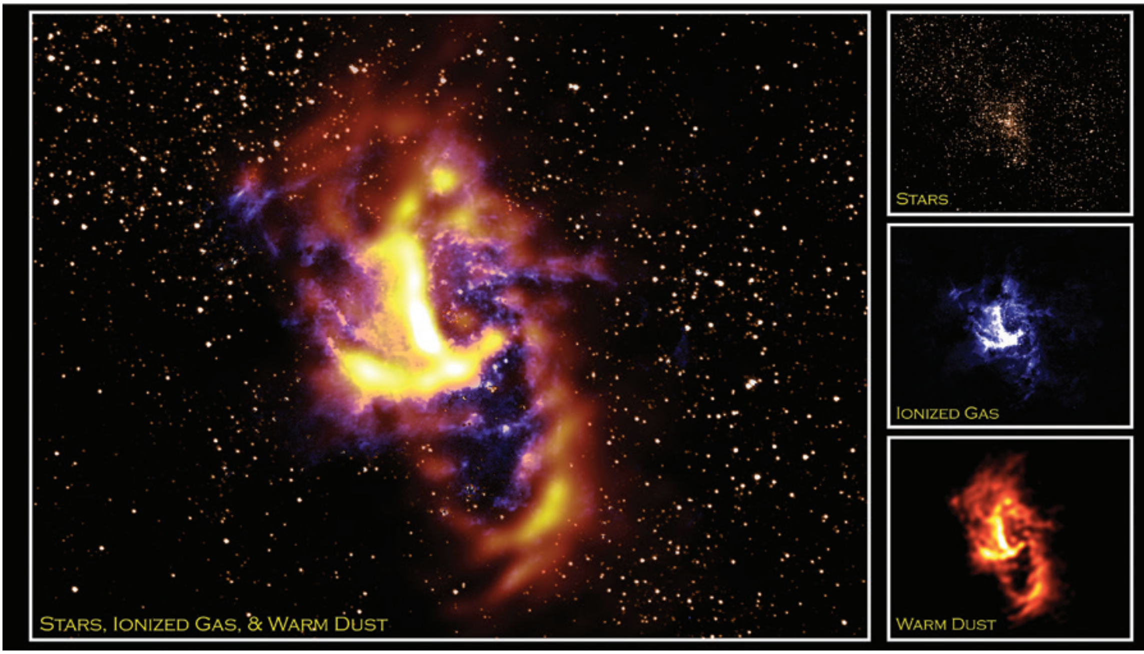


Figure 6. Images of Circumnuclear Ring (CNR) at the center of the Milky Way Galaxy. The image captured by SOFIA (lower right) shows a circumnuclear ring of dust, providing the best view of its structure since the mid-infrared view is sensitive to dust. Stars: NASA/HST/NICMOS. Ionized Gas: NASA/HST/NICMOS. Warm Dust: NASA/DLR/USRA/DSI/FORCAST Team/Lau *et al.* 2013.

Observations of the Milky Way Galaxy's Circumnuclear Ring Instrument: FORCAST

The Milky Way Galaxy's Circumnuclear Ring (CNR) is a torus of ionized gas and warm dust 10 light years in diameter orbiting about Sgr A*, the 4-million solar-mass black hole at the center of our Galaxy, 27,000 light years from Earth. Large quantities of interstellar dust and gas between us and the Galactic center make it nearly impossible to study the CNR at visible or ultraviolet wavelengths. Fortunately, radiation at infrared wavelengths can pass through the clouds of dust and gas. These images capture the infrared emission from stars (HST/NICMOS), ionized gas (HST/NICMOS), and warm dust (SOFIA/FORCAST) within the central 10 light years of the Galaxy. A cluster of massive, young stars seen at the center of the upper right image is responsible for ionizing the gas (middle right) and heating the dust (lower right) in the CNR. The SOFIA/FORCAST observations of the CNR present the highest spatial resolution images of the warm dust emission from the CNR at the far-infrared wavelengths and reveal its "clumpy" nature. Calculations predict that such clumps within the CNR should be ripped apart due to the strong tidal forces from Sgr A*, which means that the CNR will appear as a much different structure 50,000 years from now.

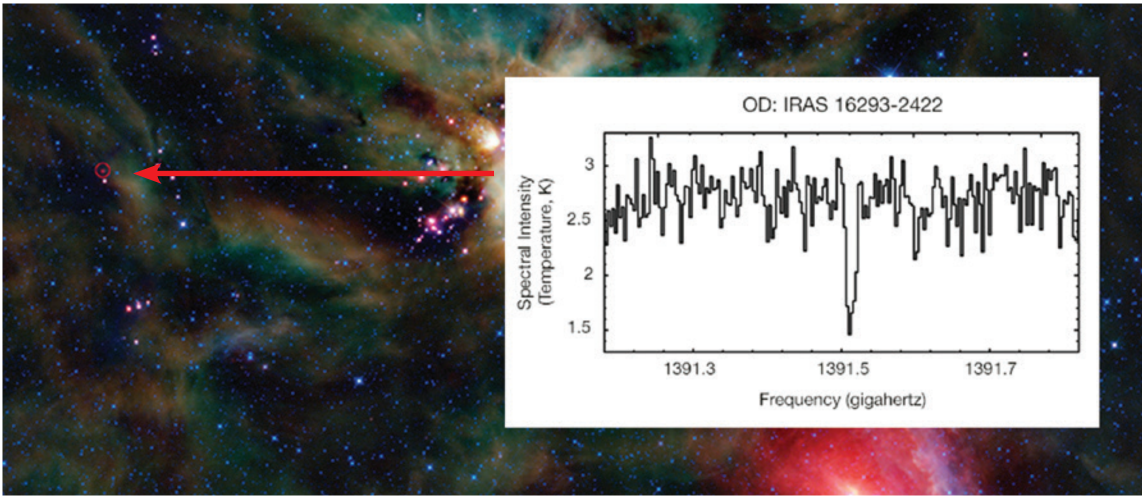


Figure 7. A deep "trough" in spectral brightness observed at a frequency of 1391.5 gigahertz (wavelength of 215.6 microns) with SOFIA/GREAT indicates abundant deuterated hydroxyl (OD) molecules in the interstellar material between Earth and a protostar at the position indicated by the arrow. **SOFIA can identify spectral fingerprints of the processes creating the universe's water at wavelengths inaccessible to any other observatory.** (Background image: NASA/JPL-Caltech/Spitzer; Spectrum: NASA/SOFIA/MPIfR/Parise *et al.* 2012, A&A 542, L5)

Detection of a New, Basic Molecule in Interstellar Space: OD Instrument: GREAT

Water (H_20) is vital to life on Earth. SOFIA can trace the formation, distribution and evolution of water and other biogenic molecules in interstellar clouds. Bérengère Parise and collaborators used the GREAT far-infrared spectrometer on SOFIA to study the formation of water in space by investigating a protostar named IRAS 16293-2422 that is embedded in the star-forming region Rho Ophiuchi (infrared image, above). Exactly how hydrogen and oxygen atoms "find each other" and bond to produce water molecules in the extreme environment of space is surprisingly complicated and not well understood. The formation of OH (hydroxyl) molecules is thought to be an important intermediate step. In the extremely cold temperatures found in the cores of molecular clouds where new stars form, oxygen prefers to combine with the heavier version of hydrogen named deuterium (D) to make OD (deuterated hydroxyl) rather than OH molecules. The area marked with a red circle, to the left of the arrow tip, is where OD molecules were detected by SOFIA. The inset shows an absorption spectrum of the OD molecule observed at a wavelength of 215.6 microns that falls in a gap not covered by any other observatory. This is the first detection of OD molecules outside of our Solar System.

The detection of OD molecules is a prime example of SOFIA's central role in understanding the processes forming water in the universe, bringing us a step closer to understanding the origins of the building blocks of life.

Successful Observation of a Pluto Occultation Instrument: HIPO

Figure 8. SOFIA's flight path (red line) during July 2011 observations of an occultation when, from Earth's view, Pluto momentarily moved in front of a distant star. The occultation provided an opportunity for SOFIA to measure the properties of Pluto's atmosphere. The grey arrow shows the track of the center of Pluto's shadow across the surface of Earth; the full shadow was about the size of Australia. SOFIA's path intersected the shadow track at the location indicated.

SOFIA has the unique capability of mobility. The observatory can operate from airbases worldwide but will primarily observe out of the NASA Armstrong Science Aircraft facility, and periodically out of Christchurch, New Zealand, to observe celestial bodies unavailable to us from the Northern Hemisphere. SOFIA's mobility will also allow it to place itself in the path of transient events such as eclipses or stellar occultations.

Ted Dunham, HIPO Principal Investigator, was a member of a group that serendipitously discovered the rings around Uranus by observing a stellar occultation. This was in 1977 onboard SOFIA's predecessor, the Kuiper Airborne Observatory. An occultation allows scientists to observe the surroundings of solar system bodies, which led, for example, to discovering rings around Uranus, and being able to measure pressure, density and temperature profiles of Pluto's atmosphere.

In June 2011, SOFIA vigilantly observed a Pluto occultation with the HIPO instrument. Two hours before the occultation, MIT contacted SOFIA in-flight with new coordinates of the center of Pluto's shadow. After recalculating and filing a revised flight plan, SOFIA's flight crew and science team anxiously waited 20 minutes before receiving permission from air traffic control to alter their flight path. The figure above maps SOFIA's flight path from that evening, including the last minute changes to target Pluto's shadow. The ability to rapidly change course to observe the Pluto occultation served to galvanize SOFIA's unique capability for studying transient events. This map exemplifies the observatory's potential: long range, flexibility of flight configuration, and zeroing in on an ephemeral event.

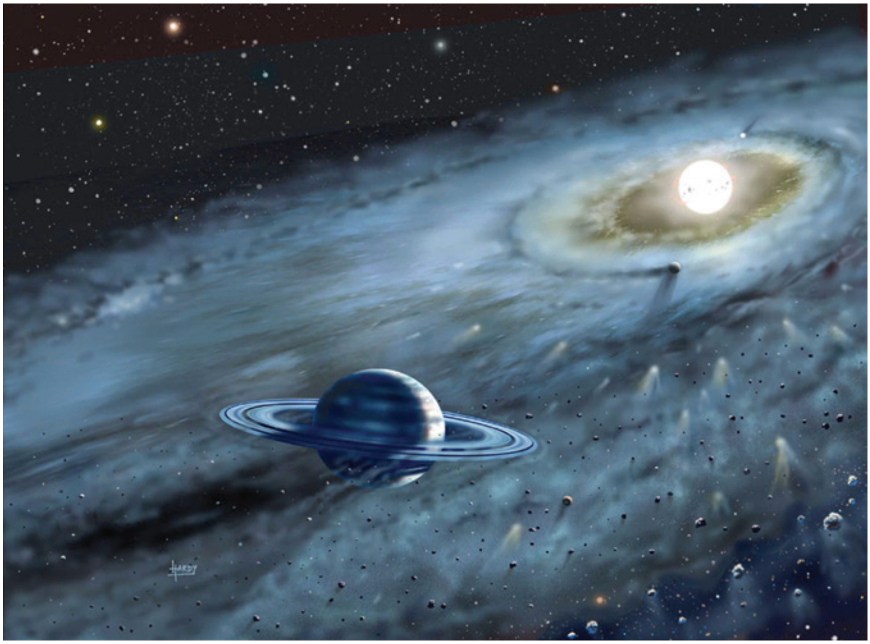


Figure 9: Star and planet formation (© David A. Hardy/www.astroart.org)

Future Science

With unique infrared capabilities complementing other observatories, SOFIA will deepen the grand narrative of our understanding of the universe.

The Formation of Stars and Planets

The formation of stars and planets is a central problem in astrophysics. On the largest scales, star formation is a key component of galaxy evolution. On smaller scales, the linked processes of star and planet formation provide the foundation for understanding both our own Solar System and the wide diversity that we are finding among other planetary systems. The cycling of gas and dust from the interstellar medium (ISM) into stars and planets and back into the ISM occurs in dust-enshrouded environments and at relatively low temperatures. Thus, most emitted radiation emerges at mid-IR to sub-mm wavelengths. SOFIA's unique capabilities in this wavelength range are vital for star formation research in general, and especially for studies of massive star formation, circumstellar disks, and astrochemistry.

The Interstellar Medium of the Milky Way

The interstellar medium (ISM) plays a central role in the evolution of galaxies as the birthsite of new stars and the repository of evolved stars' ejecta. The formation of new stars slowly consumes the ISM, locking it up for millions to billions of years in stellar interiors. As stars age, stellar winds and supernova explosions inject nucleosynthetic products into the ISM, slowly increasing its metallicity. This constant recycling and enrichment drives the evolution of a galaxy's gas and dust and hence changes its emission characteristics. Since most of a galaxy's emission from the ISM is at mid- to far-IR wavelengths, SOFIA is uniquely suited for galactic ISM studies. In particular, SOFIA's mapping capability and spectroscopic instrument complement are well suited for spectral imaging of bright sources and extended regions of ISM in the Milky Way and nearby galaxies.

The Galactic Center

The center of our Galaxy is a few hundred times closer than even the nearest active galaxies, enabling uniquely detailed studies of phenomena found only in galactic nuclei, including extremely warm dense clouds, strong magnetic fields, and a supermassive black hole. Infrared observations, which first opened the window of visibility on the Galactic Center, are particularly valuable for investigating the many questions about this complex region. The Galactic Center provides a template by which more distant galactic nuclei may be understood, and SOFIA is a crucial platform for studying the processes and phenomena occurring therein.

Star Formation in Nearby Galaxies

A key challenge for extragalactic astrophysics is understanding the star-formation history of external galaxies, and the investigation of the interstellar medium (ISM) in galaxies is essential to that goal. Far-IR fine structure lines are excellent probes of both the physical conditions in understanding ISM and properties of the stellar radiation field within galaxies. SOFIA observations of these and other lines at unprecedented spatial resolution will enable studies of the variations in ISM conditions in nearby galaxies as a function of location and distance from nuclei and spiral arms.

Planetary Science

A general but incomplete picture has emerged over the past few decades regarding how the Earth and the rest of the Solar System formed, bolstered by the discovery of more than 1,000 extrasolar planets orbiting other suns. It is less well known how the planet formation processes set the stage for life to develop on Earth and perhaps also on other Solar System bodies. SOFIA's unique capabilities — including the ability to observe planetary occultation events — will enable important observations of Venus, Mars, the Jovian planets and their moons, and primitive bodies containing material little altered since the Solar System's birth. These studies will help fill gaps in our understanding of the formation of our Solar System and even life on Earth.

Instrumentation Development

The scientific success of SOFIA depends on the ability to replace and improve on current instrumentation. The observatory is a platform for innovation. Focal plane technology is still advancing rapidly in the far-IR, and major improvements in detector sensitivity and array size are anticipated. Opportunities to propose for development of later generations of SOFIA science instruments will enable new science that was previously impossible with existing technology.

For More Information

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www.nasa.gov/SOFIA

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