



“The Case For SOFIA”

Stratospheric Observatory for Infrared Astronomy

NASA Ames Research Center
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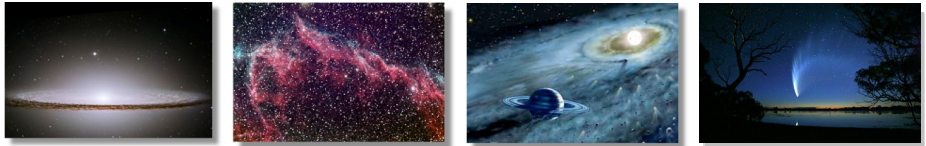
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Second Printing

I. Introduction



The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a powerful new ship in NASA’s research fleet developed in partnership with the German Space Agency, DLR. As the only flying astronomical observatory in the world, SOFIA will impact 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 will unite science as well as scientists.

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



Figure 1. NASA’s SOFIA infrared observatory with chase plane during the first series of test flights to verify the performance of the modified Boeing 747SP. From the NASA Dryden Flight Research Center Photo Collection.

SOFIA consists of a German-built 2.7-meter telescope embedded in a modified Boeing 747-SP aircraft supplied by NASA (Figure 1). Observing while flying at altitudes up to 45,000-feet, 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 μm .

Expected to fly for two decades, SOFIA will offer international science teams approximately 1,000 cloud-free high-altitude science observing hours per year. More than 100 science proposals per year will be 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.

Humanity has pondered our origins and destiny from the earliest times. Today, our wonder is drawn to the journey of matter through the Universe, perpetual dynamism as the basic building blocks of life are formed and reformed, destroyed and used again to form new stars and other heavenly bodies. Clues to the physics and chemistry of cosmic evolution lay scattered about vast landscapes of space.

SOFIA will help elucidate the details of this journey, from faraway galaxies to Venus next door. Heavenly bodies large and small emit detectable energy signatures, details of a Universe beyond our material reach. As SOFIA reads these signals, astronomers can trace the journey of matter from clouds to stars and planets, and back again. Infrared observations of this matter will further shape our understanding of the formation and evolution of:

- Galaxies, including our own, and the role massive black holes play in their development
- Stars, including the chemistry and physics of their origin material
- The basic building blocks of life, and the survivability of such for new planetary systems
- Planetary systems, and the original conditions of our own Solar System
- Icy bodies in our Solar System and the incorporation of volatile materials into the terrestrial planets

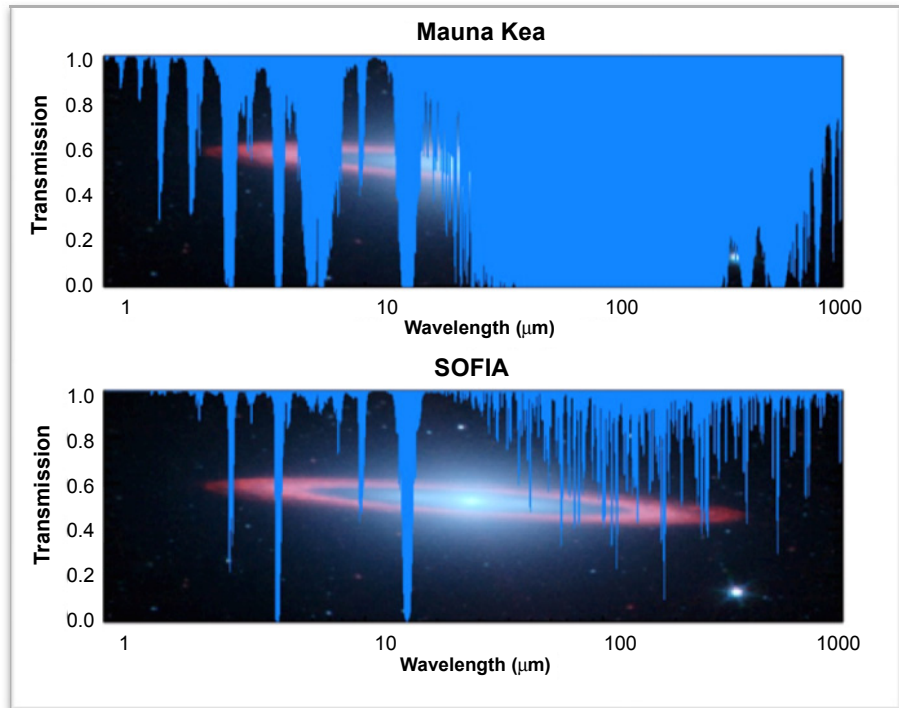


Figure 2. The typical atmospheric transmission at an altitude of 45,000 feet as compared to the transmission on a good night at Mauna Kea (13,800 ft. MSL). This figure reveals the atmospheric window through which SOFIA will peer. Background image: IRAC false color image of the Sombrero Galaxy, courtesy of NASA/JPL-Caltech.

SOFIA has one huge advantage over ground-based or space telescopes — it can fly anywhere on the globe at any time to capture transient events that can be viewed only from certain locales, such as occultations of stars by planets that reveal the structure of planetary atmospheres. It will be called upon to witness out-of-the-ordinary transient events, such as supernovae, comets falling toward the Sun and planets, or asteroids and comets approaching the vicinity of Earth.

Upon lift-off, spacecraft carry outdated technology skyward due to the long lead times from selection to launch. The first generation of nine US and German instruments will cover 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. In a sense, it was designed to be re-designed. 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. Whether they become astronomers or move into related technical fields, the technical training they receive here will serve us well, as humans embracing our technological future.

To the non-specialist or non-scientist, the premise of SOFIA is simple: Astronomers can trace the far-flung "energy fingerprints" of matter, as the universe shapes and reshapes heavenly bodies and the diffuse environments that bear them. The search for life's physical and chemical origins has matured over the last decade and engaged a curious public just at the time SOFIA and other missions will help us understand the pre-Earth phases of Astrobiology. This curiosity can be directly addressed with SOFIA — it is the only major astronomical research observatory designed from the start to bring non-scientists into close contact with scientists in a research environment. In a competitive global environment, scientific literacy is a national security and economic issue for many countries, including SOFIA's partners, the US and Germany. SOFIA will serve varied audiences, for the citizen-scientist and scientist-citizen. A citizenry trained in evidence-based inquiry is well suited to thrive far beyond professional science. The SOFIA program will:

- Fly teachers and other educators so they can take their experience and inspiration back to the nation's classrooms and science museums.
- Prepare educational material for grades K-14, in physics, astronomy, and astrobiology.
- Broadcast the SOFIA mission publicly in the scientific and general media, and over the myriad public electronic channels.
- Offer SOFIA internships to undergraduates for work in both the US and Germany.

With unique capabilities, and as a complement to peer missions (Figure 3), SOFIA will deepen 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. The remainder of this paper serves as an outside-in introduction, starting with external galaxies and going into the solar system, of only a few representative examples of the rich science return that can be expected from SOFIA over its 20-year operational lifetime.

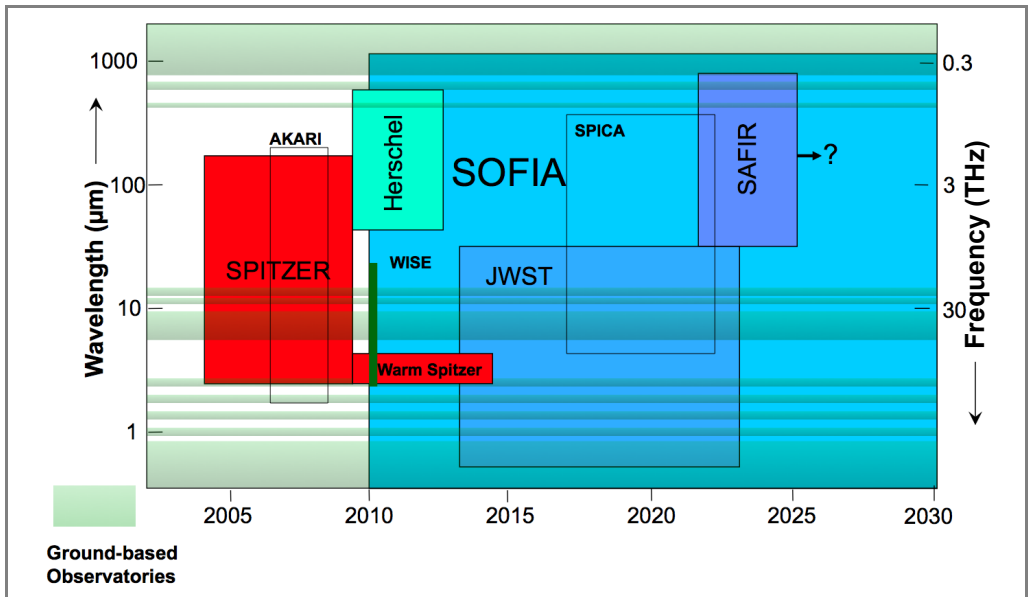


Figure 3. SOFIA's flight lifetime and time-frame will make it a premiere facility for doing far-IR and submillimeter wave astronomy from 2010 until the mid 2030s. It will be the only facility available for wavelength coverage in the 28-1200 μm spectral region and for high resolution spectroscopy during much of that period. The SPICA and SAFIR missions have yet to be formally approved. The length of the SAFIR mission is undetermined at present.

II. Galaxies and the Galactic Center

Starburst History

Interstellar Medium

Galactic Center



Just as the last 100 years of biology established that something as tiny as a molecule can affect something as large as a biped mammal, astronomers now understand that an environment as large as a galaxy sets conditions for something as small as a Solar System. The dynamics by which this occurs are less clear.

Starburst History

The first of our example “stories” that SOFIA can tell begins with galactic-scale events that occurred long ago. SOFIA will observe faraway galaxies frozen, from our perspective, during their peak star formation period. These galaxies have red shifts between 0.3 and 1.1. Such a range provides a look-back through time, from close to the present to galaxies with “starburst” peaks going back more than halfway through the history of the Universe. The observatory can detect the brightest infrared lines from these sources, with spatial resolution significantly higher than previous observatories operating at these wavelengths. This capability will provide observations to constrain the strength and spatial extent of starbursts, addressing questions, such as whether or not these regions, where exceedingly large numbers of stars form, are confined to localized areas or are found galaxy-wide. Such a survey is expected to be critical to understanding the star formation history of the Universe.

Extragalactic Interstellar Medium (ISM)

High-spatial resolution images will capture interstellar matter winding through the arms of other galaxies. SOFIA will investigate the role these spiral structures play in star formation – and the interaction between young stars and their natal environment. This mission provides a new opportunity to probe with great sensitivity the physical conditions of other galaxies’ ISM, using specific lines which serve as the dominant coolants in the balance of temperature, and will allow astronomers to estimate the density and mass of various structures and the elemental abundances within them.

Galactic Center

SOFIA will unlock data from the nearest galactic center — our own — and use it to build a template for how galactic nuclei work in general. Phenomena we see there emerge from the interaction of many things — the central black hole, massive stars, dense clouds, strong magnetic fields, an intense x-ray background and other types of high-energy radiation. Mysteries endure about the nature of these interactions.

Astronomers have significant questions concerning the mechanism by which molecular clouds heat up in the central molecular zone of our own galaxy. The temperatures can be as great as 500K in places, which is significantly hotter than expected for a region of this size. The leading candidates are shock waves — arising either from cloud-cloud collisions or from internal supersonic motions from violent events within the clouds — and X-rays. These explanations can be studied through the comparison of specific far infrared emission lines, which SOFIA will be able to measure readily. The ratio of these lines will point to the extent and influence of these events. Understanding which mechanism dominates and where will aid in the study of other galactic centers.

Powerful magnetic fields emanate from the central molecular zone of our own galaxy. Clouds that have been studied show remarkably uniform magnetic alignment in polarized dust grains, but the complete story of how and why this occurs is not understood. SOFIA will observe many such clouds, documenting the spatial fluctuations in the magnetic field’s direction, which provide clues to the production mechanism. Its instruments can measure directional changes with five times better spatial resolution than has so far been available, taking the understanding of magnetic fields to a level where detailed models can be used to predict and describe them in a more general sense. Such measurements are critical for our understanding of cloud dynamics, star formation, and the strong inter-cloud magnetic field.

III. The Interstellar Medium of the Milky Way

Stars and Environs

Polycyclic Aromatic Hydrocarbons (PAHs)

Origin of Dust



The Interstellar Medium contains an elemental record of the generations of stars that have lived and died since the galaxy’s birth. SOFIA will observe spectra of bright sources and extended regions, probing the physics and chemistry of both. The physical processes governing how stars interact with their environments, the origin of dust, and the role of large, complex carbon molecules — notably polycyclic aromatic hydrocarbons (PAHs) — will be explored. PAH molecules are so ubiquitous that they can be used as a “dye” to trace the chemistry of prebiotic molecules within star forming regions, allowing ever deepening views into the shrouded nurseries where stellar, and eventually planetary systems, form.

Stars and Environs

Stellar radiation transforms its nearby environment, ionizing gaseous atomic hydrogen and driving the chemistry of star forming regions with far-infrared photons. SOFIA will read the infrared signatures of these massive star-forming pockets and map how they change with physical conditions, such as density, metallicity, and temperature. SOFIA can see all of the

important spectral signatures of infrared-emitting atoms and molecules, many which are implicated in astrobiology.

Dust

Interstellar Dust is an essential component of the Interstellar Medium (ISM) and the clouds from which stars form. Dust grains form within the outflow regions of stars at the end of their life, and are modified both chemically and physically throughout their tenure in the ISM. Depending upon their locale, dust grains provide effective shielding from harsh interstellar radiation for high-density clumps trying to become newborn stars. Along with interstellar gas, dust grains provide the very foundation upon which interstellar ices form. Energetic processing of these simple ices yields the complex chemistry that finds its way into planetary systems and eventually into living beings, including ourselves.

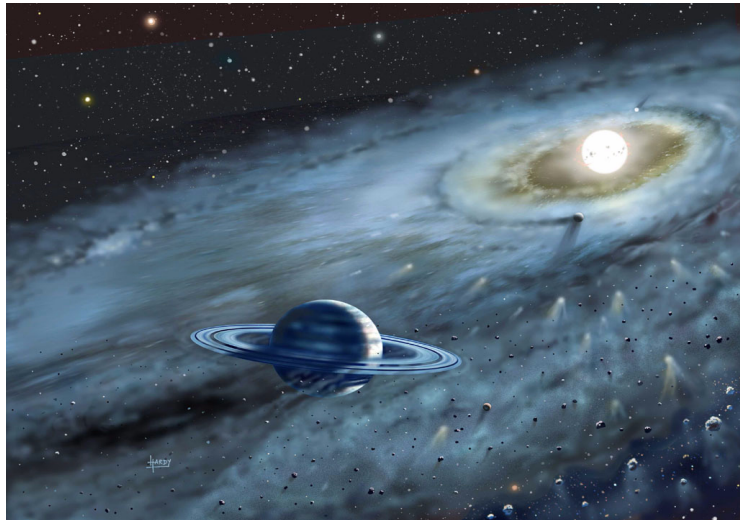
Polycyclic aromatic hydrocarbons (PAHs) are such an example. PAH's form from the chemical inventory that builds up in the protected environment of a dense, dark cloud. PAH chemistry that occurs in and around dense clouds may be at the base of the reservoir of prebiotic organic compounds available to evolving planetary systems, a key motif of astrobiology. Understanding the chemistry of interstellar dust and the environments where dust survives will provide essential pieces of the puzzle of how the universe works, and this is a challenge SOFIA is ideally suited to meet.

IV. The Formation of Stars and Planets

Massive Stars

Oxygen Detection

Water and its Isotopes



A century ago no one understood why stars shine. Today, astrophysicists explain energy production in stars with great precision. Our current unknowns concern the cycles by which stars form, ignite, and replenish the clouds with gaseous remains and the heavier nuclei synthesized in their cores. Matter condenses into young stellar objects and the thick, dusty, donut-shapes that obscure them. Further collapse into proto-planetary disks initiates development of solar systems, as happened 5 billion years around the Sun.

Massive Stars

SOFIA will greatly contribute to our understanding of the details of how gas and dust yield the macroscopic order of star and planetary systems. As part of the more general star formation investigations that will be undertaken, SOFIA will focus on understanding how the most massive stars form. These stars, although not numerous, greatly impact large areas of the galaxy by virtue of their exceedingly higher temperatures. By collecting comprehensive data on hundreds of massive stars, correlations of their spectra with stellar mass, age and metallicity will provide a much clearer understanding, of how core collapse occurs. Improvement in models requires broader spectral energy distributions of nascent massive stars, which are

dark in the near- and sometimes mid-infrared. SOFIA will meet this need by observing massive stars with higher spatial resolution than previous missions and with the broad spectral coverage (25-300 microns) required.

Where is the Oxygen?

Throughout the varied regions of the galaxy the amount of oxygen seen, compared to the other elements, is relatively uniform. This is not true however in star formation regions, where recent observations can account for only 70 percent or so of the oxygen that would have been expected. Oxygen is a pivotal component for planets and life, found in water, in terrestrial rocks, and in complex organic molecules, which makes finding the full complement of oxygen of great interest. Detection of H₂O and OH lines unique to SOFIA's infrared vision will likely reveal the missing oxygen, and by inference, use it to trace the important chemical pathways.

Water

H₂O is essential to the formation of life. SOFIA can trace the formation, distribution and evolution of water and its isotopes from giant molecular clouds to the planet-forming zones of disks, gleaning, among other things, where ices exist in various states (amorphous and crystalline, for example) as we trace it from the ISM to planet-bearing disks.

V. Planetary Science

Comets

Near-Earth Asteroids

Venus

Atmosphere-bearing moons



Comets, near-Earth asteroids, atmosphere-bearing moons (such as Titan), and planets (notably Venus), betray evidence of their own origins and, by extension, that of the Solar System. Water and organic materials are clues to how solar system bodies formed, how those ingredients rained down on early Earth, and how the stage was set for the eventual appearance of life on our planet.

Comets

The Stardust and Deep Impact missions drew a complicated picture of comets and solar system evolution. New models predict that dynamic mixing led to greater diversity among comets, more so than has been previously expected. SOFIA will build on these results and test new hypotheses by tracking the water, mineralogy, and organic content of comets, assembling a taxonomy of the more than 60 comets available to observation over its lifetime. Combined with dynamical modeling and data from other missions, this catalog will delineate the water and pre-biotic organics likely delivered to the early Earth. Water is the principal volatile in comets. The isotopic composition of water, which SOFIA will investigate, is a key diagnostic criterion for understanding the origin of comets.

Venus

By circumstance, Earth’s sister planet has never been thoroughly explored with broadband, high-resolution spectroscopy, but SOFIA will open the door to studies of many molecules predicted by theory. SOFIA can play the role of a Venus-focused spacecraft with the potential for discoveries in atmospheric chemistry and the ability to map dynamics well below the visible haze layer.

Comparable to the Earth in mass and probably initial volatile content, Venus may have lost nearly all its hydrogen to a fierce runaway greenhouse effect. Understanding its initial conditions would provide a crucial point in unraveling the formation of the Earth and other inner planets. Venus’ slow rotation gives it unusual atmospheric dynamics, including a puzzling “super-rotating” middle atmosphere that transports substantial energy from the day-side to the night-side. With its high-resolution spectrographs, SOFIA can uniquely observe molecules key to understanding the unusual Venusian atmospheric chemistry.

Venus is available to SOFIA investigations for six months around its maximum elongation from the Sun both before sunrise and after sunset. SOFIA will become the facility of choice for study in spectral regions unavailable from the Earth — at least until another spacecraft with a mid- to far-infrared high-resolution spectrometer visits Venus. None is currently approved to do so.

VI. Conclusion



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 will be the world's only flying observatory.

SOFIA's vision, from Earth's sister planet to faraway galaxies, will support a vast number of potential investigators over its expected two-decade lifespan. The epic questions that drive NASA's space science program poise SOFIA for service to humankind, providing a platform for collaboration, innovative technology, and scientific discovery.

This overview was designed to provide a broad-brush rationale for the case for SOFIA, designed for a general audience. A more detailed document written for scientists, the “Science Vision for Stratospheric Observatory for Infrared Astronomy,” includes representative descriptions of science investigations, detailed technical capabilities, and illustrations of the synergistic relationship SOFIA will have with other astronomical missions.

