The joint U.S. and German SOFIA project to develop and operate a 2.5-meter infrared airborne telescope in a Boeing 747-SP is now in its final stages of development. Flying in the stratosphere, SOFIA allows observations through the infrared and submillimeter region, with an average transmission of \( \gtrsim 80\% \). SOFIA is characterized by a wide instrument complement ranging from broadband imagers, through moderate resolution spectrographs capable of resolving broad features due to dust and large molecules, to high resolution spectrometers suitable for kinematic studies of molecular and atomic gas lines at \( \text{km/s} \) resolution. This broad range in instruments will enable SOFIA to make unique contributions to a broad array of science topics. First science flights will begin in 2009 and the observatory is expected to operate for over 20 years. The sensitivity, characteristics, science instrument complement, and examples of first light science are discussed.

**Keywords:** Submillimeter; Infrared; Airborne Astronomy

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### 1. Introduction

The Stratospheric Observatory For Infrared Astronomy (SOFIA) is NASA’s and the German Space Agency’s (DLR) premier observatory for infrared and submillimeter astronomy. A Boeing 747-SP aircraft will carry a 2.5-meter telescope designed to make sensitive infrared measurements of a wide range of astronomical objects. It will fly at and above 12.5 km, where the telescope will collect radiation in the
wavelength range of 0.3 \( \mu \text{m} \) to 1.6 mm. SOFIA is being developed and operated for NASA and DLR by the Universities Space Research Association (USRA).

The telescope and 20\% of operations will be supplied by Germany through contracts with DLR. The University of Stuttgart has been awarded the contract to run the Deutsches SOFIA Institut (DSI). The development of the science instruments to be installed on the SOFIA telescope will be the responsibility of the U.S. and German science communities. In the U.S., science instruments will be designed and built at universities and national centers through a USRA led peer review process.

2. Science Operations

SOFIA will see first light in 2009, and is planned to make more than 120 scientific flights per year of at least 8 to 10 hours in duration. SOFIA is expected to operate for at least 20 years, primarily from Moffett Field in California, but occasionally from other bases around the world, especially in the Southern Hemisphere. SOFIA will fly above 12.5 km, where the typical water vapor column density is less than 10 \( \mu \text{m} \); typical transmission is shown in Figure 1. It is clear that, except for a few very narrow bands in the mid-infrared that are completely blocked by telluric CO\(_2\), the infrared and submillimeter window really opens up at aircraft altitudes.

![Image](https://example.com/sofia_transmission.png)

**Fig. 1.** The typical atmospheric transmission of SOFIA as compared to a good night at Mauna Kea. From 1 to 1000 \( \mu \text{m} \) the average transmission is \( \gtrsim 80\% \) except in the center of absorption lines due to mostly H\(_2\)O and CO\(_2\). Background image: IRAC false color image of the Sombrero Galaxy, courtesy of NASA/JPL-Caltech.

The SOFIA Science and Mission Operations Center (SSMOC), to be operated by USRA, will be located at NASA Ames Research Center at Moffett Field in the same hangar that will house SOFIA. The SOFIA Program will support approximately 50
investigation teams per year, selected by a peer reviewed proposal process.

The finished telescope has been mated into the modified aircraft (Figure ??) and was tested in 2004. First test flights of the observatory will occur in 2007, and first science in 2009.

Fig. 2. The SOFIA telescope in the modified 747SP aircraft. The 2.5-meter primary mirror is behind the red cover. The cavity door, which follows the telescope, is in the open position and shows the aft ramp to capture the boundary layer over the cavity.

3. SOFIA First Generation Instruments

A total of nine instruments have been selected and are now under development (see Table 1). The selection includes three Facility Class Science Instruments (FSI): HAWC, FORCAST, and FLITECAM. These instruments will be maintained and operated by the science staff of the SSMOC for the general science community. In addition, there are six Principal Investigator Class (PI) Science Instruments, which will be maintained and operated by the PI teams at their home institutions. General investigators will be able to propose for these instruments in collaboration with the PI team. Two of the PI Class instruments are being developed in Germany.

One great strength of an airborne observatory is that science instruments can be regularly exchanged. In addition, compared to space-based missions, much larger and more massive instruments can be flown. Likewise, heat dissipation and power consumption are of lesser concern than for satellites. SOFIA will take full advantage of these aspects and the first generation instrumentation is very diverse. This is illustrated in Figure ?? which shows the discovery space of SOFIA. SOFIA’s nine first generation instruments cover the full wavelength range from the visible to the near, mid, and far-infrared and submillimeter and, in spectral resolution terms, range from imagers with narrow photometric bands, to moderate resolution.
Table 1. SOFIA First Light Instruments

<table>
<thead>
<tr>
<th>PI</th>
<th>Institution</th>
<th>Name</th>
<th>Type of Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. Dunham</td>
<td>Lowell Observatory</td>
<td>HIPO</td>
<td>High-speed Imaging Photometer for Occultations 0.3 - 1.1(\mu)m</td>
</tr>
<tr>
<td>I. McLean</td>
<td>UCLA</td>
<td>FLITECAM</td>
<td>Near-IR Camera 1 - 5(\mu)m; GRISM (R = 2,000)</td>
</tr>
<tr>
<td>J. Lacy</td>
<td>Univ. of Texas</td>
<td>EXES</td>
<td>Echelon Spectrometer 5-28(\mu)m; (R = 10^5, 10^4,) or 3,000</td>
</tr>
<tr>
<td>T. Herter</td>
<td>Cornell</td>
<td>FORCAST</td>
<td>Mid IR Camera 5 - 40(\mu)m</td>
</tr>
<tr>
<td>D.A. Harper</td>
<td>Univ. of Chicago</td>
<td>HAWC</td>
<td>Far IR Bolometer Camera 50 - 240(\mu)m</td>
</tr>
<tr>
<td>A. Potlitsch</td>
<td>MPE, Garching</td>
<td>FIFI-LS</td>
<td>Field Imaging Far IR Line Spectrometer 40 - 210(\mu)m; (R \simeq 2,000)</td>
</tr>
<tr>
<td>S. Moseley</td>
<td>NASA GSFC</td>
<td>SAFIRE</td>
<td>Imaging Fabry-Perot Bolometer Array Spectrometer 145 - 655(\mu)m; (R = 1,000 - 2,000)</td>
</tr>
<tr>
<td>R. Güsten</td>
<td>MPIfR, KOSMA</td>
<td>GREAT</td>
<td>Heterodyne Spectrometer 60 - 200(\mu)m; (R = 10^4 - 10^8)</td>
</tr>
<tr>
<td>J. Zmuidzinas</td>
<td>Caltech</td>
<td>CASIMIR</td>
<td>Heterodyne Spectrometer 200 - 600(\mu)m; (R = 10^5 - 10^8)</td>
</tr>
</tbody>
</table>

Fig. 3. SOFIA’s first generation of instruments shown in a plot of log spectral resolution vs. log wavelength.

spectrometers geared towards studies of broad dust and molecular features, to high resolution instruments capable of velocity-resolved gas phase line studies.

Another advantage of an airborne observatory, as compared to a space-based mission, is the ability to rapidly incorporate instrument improvements and other instrument upgrades. In this way, instrumentation can quickly react to new technological developments. Technology is still expanding rapidly in the far-infrared and major advances in sensitivity and array size can be expected. SOFIA will support a technology development and new instrumentation program which will essentially provide a new instrument complement and thus a new mission every \(\sim 10\) years at the modest cost of the instrument development program.

One disadvantage of an airborne mission compared to a space-based mission is the much higher background. Nevertheless, SOFIA will be about an order of magnitude more sensitive than the IRAS space mission and of course will have a
factor >5 better spatial resolution due to its larger telescope aperture. At high spectral resolution, SOFIA will match or be more sensitive than the ISO space mission. In addition, no space-based mission is presently envisioned with a spectral resolution exceeding 3,000 in the 3 to 150\(\mu\)m range, the "home" of many of the important atomic and ionic finestructure lines as well as ro-vibrational transitions of many simple molecules, including H\(_2\)O, CH\(_4\), and C\(_2\)H\(_2\).

4. SOFIA is an Observatory with Something for Everybody

Many of the most interesting objects in the universe are shrouded in darkness, hidden from view by dense layers of obscuring dust and gas. This includes such diverse objects as the black holes in the centers of galaxies and budding stars and their planetary systems. Information on these objects and their inner workings must then be gleaned from their interaction with their environment. In essence, the obscuring dust and gas "down converts" energetic photons from the central object into infrared and submillimeter line and continuum radiation. SOFIA, with its diverse complement of instruments, is uniquely suited to study deeply embedded objects and determine their role in the evolution of the universe. As illustrated in Figure ??, SOFIA will be able to contribute to a wide variety of science topics. These focus on the formation of stars and planetary systems, the characteristics of dwarf-planets at the edge of our Solar System and what that tells us about the origin and evolution of the solar system, the death of stars and the enrichment of galaxies by their ashes, the black hole in the center of our galaxy, and the role of star formation and black hole activity in the nuclei of starburst galaxies. Below, we discuss in more detail some of the first science that may be done with SOFIA.

Fig. 4. The same plot as in Figure ?? with the science topics overlayed in the appropriated position.
4.1. Exploring the Kuiper Belt with Stellar Occultations

Inhabiting the region of the solar system beyond Neptune, Pluto and many other newly defined Dwarf Planets in and beyond the Kuiper Belt represent some of the oldest material known in the solar system. Hence knowledge of their fundamental properties is essential to our understanding of the origin and early evolution of the outer solar system. Stellar occultations can probe Dwarf Planets with a spatial resolution of a few kilometers, and from these data we can establish their diameters, detect or place limits on any atmospheres, and search for potential nearby companions. Because of the small zones of visibility of these events on Earth and the faintness of most occulted stars, a large, mobile telescope offers nearly two orders of magnitude more opportunities than other approaches. SOFIA observations of ten stellar occultations of the four brightest potential Dwarf Planets can be done with HIPO and FLITECAM. (See Elliot et al 2005)

4.2. Precise Photometry of Extrasolar Planet Transits

SOFIA will fly above most of the scintillating component in the Earth’s atmosphere and hence can be expected to yield very precise photometric measurements of stars. We anticipate that very high quality transit data can be obtained with SOFIA using the HIPO and FLITECAM science instruments. Precise photometric observations of transiting extrasolar planets can provide a wealth of data on the nature of these objects. Results such as planetary radius, orbital inclination, stellar limb darkening, evidence for planetary satellites or rings, and atmospheric composition can be found from the transit observation alone. When combined with high quality radial velocity data the mass and density of the planet can be determined. Infrared observations of the secondary minimum provide a means to determine the temperature of the planet and allow limits on the orbital eccentricity to be defined. Perturbations by other planets in the system can be found by variations in transit timing over a period of years.

Initially, this work will focus on the two or three brightest known transiting planets. The ongoing spectroscopic planet search programs and several ongoing transit search programs designed specifically to find objects bright enough for detailed follow-up work are expected to add numerous objects to this list over SOFIA’s lifetime. (See Dunham et al 2005)

4.3. Water in Planet-Forming Disks

Because of angular momentum conservation, protostars will be surrounded by circumstellar (CS) gaseous disks (Shu et al 1987). These disks are natural sites for planet formation. It is generally thought that water plays a major role in the formation and early evolution of planetary systems. In particular, water is the dominant reservoir of oxygen under nebular conditions and hence ice condensation will dominate the mass budget of newly-formed planetesimals. It is usually thought that
the cores of giant planets are formed beyond the so called snow line: the boundary where the temperature falls below 170 K, the sublimation temperature of H$_2$O ice (Sasselov and Lecar 2000). The origin and distribution of water in the inner protoplanetary disks, of course, also has likely implications for our understanding of the abundance of water on terrestrial planets in the habitable zones around stars.

Observational studies of planet-forming systems have exclusively focused on the mid-infrared continuum spectrum due to thermal emission by dust in the disk, basically because detection of molecular emission lines from the gas is difficult with present instrumentation (e.g., Mundy et al 2000). EXES on SOFIA will be uniquely suited to study the distribution of water in the disks around young protostars. Specifically, EXES is geared towards high resolution spectroscopy of the ro-vibrational transitions of H$_2$O in the mid-infrared. These lines are expected to be in emission - due to pumping by stellar photons - for face-on disks or in absorption against the stellar photosphere for highly inclined disks. The strength of the lines will directly provide the temperature and column density of water. While the spatial resolution of SOFIA will be limited, the resolved line profile provides, in combination with Kepler’s law, the distribution of the water in the emitting layers of the disk. Studies of water lines in the 2.0 to 2.4 μm window have revealed the power of such molecular line studies but such studies are of course limited to very hot gas close to the protostar. The 6μm region on the other hand is sensitive to the lukish warm gas in the terrestrial planet zone and near the snow line. We note that studies of the pure rotational lines (at submillimeter wavelengths) are either hampered by severe beam dilution or by telluric absorption.

4.4. Star Formation and the Interstellar Medium of Galaxies

The interstellar medium (ISM) plays a central role in the evolution of galaxies as the birthsite of new stars and the repository of old stellar ejecta. The formation of new stars slowly consumes the ISM, locking it up for millions to billions of years. As these stars age, the winds from low mass, asymptotic giant branch stars (AGB) and high mass, red supergiants (RSG), and supernova explosions inject nucleosynthetic products of stellar interiors into the ISM, slowly increasing its metallicity. This constant recycling and associated enrichment drives the evolution of a galaxy’s visible matter and changes its emission characteristics. To understand this recycling, we have to study the physical processes of the ISM, the formation of new stars, the injection of mass by evolved stars, and their relationships on a galaxy-wide scale. Dust and gas play a major role in these processes and hence SOFIA with its wide wavelength coverage and high spectral resolution capabilities is destined to play a dominant role in this field.

FLITECAM, FORCAST, and HAWC will provide detailed, broad/narrow band studies of the spectral energy distribution of active regions of star formation and known stellar death sites such as supernova remnants and AGB and RSG stars. Follow-up studies with SOFIA’s moderate and high resolution spectrometers will
probe the detailed composition of the gas and dust. Together, this data will allow astronomers to derive the density, temperature, chemical, and luminosity structure of these types of regions. Of specific importance are the atomic fine structure lines of [OI] at 63 and 145\,\mu m and of [CII] at 158\,\mu m. These lines are bright in regions illuminated or shocked by massive stars and their outflows. The GREAT instrument on SOFIA will be the only means to resolve these lines at the sub-km/s level and hence probe in detail the physical conditions in these regions as well as their kinematics.

4.5. The Interstellar Deuterium Abundance

Deuterium was formed in the Big Bang; its abundance provides strong constraints on the physical conditions during the first few minutes of the universe’s expansion. As stars form, deuterium is lost due to nucleosynthesis when material is cycled through stellar interiors in the course of galactic chemical evolution. Deuterium is thus potentially a key element for probing the origin and evolution of the universe as well as the star formation history of the universe. The 3 THz (100\,\mu m) channel on GREAT is designed to measure the ground state transition of HD, the main reservoir of deuterium in molecular clouds, at sub-km/s resolution. HD will be seen in emission in the warm gas associated with photodissociation regions and interstellar shocks, and in absorption toward bright background sources. Observations of a wide sample of sources will probe the cosmologically important D abundance and its astation by nuclear burning in stars throughout the galaxy.

There is no other observatory with the appropriate wavelength coverage and spectral resolution required for this study. (See Güsten 2005)

4.6. The Black Hole and the Circumnuclear Disk at the Galactic Center

A $4 \times 10^6 M_\odot$ black hole has been shown to exist in the core of the Milky Way (Ghez et al 2000, Genzel et al 2000). SOFIA, with a number of instruments, will be very well suited to study the material falling into the black hole and make observations of the emission from the circumnuclear disk region surrounding it.

The circumnuclear disk (CND) orbiting the supermassive black hole at the Galactic Center at a distance of 1 to 5 parsecs holds the key for understanding the long-term activity of this unique and important region in our Galaxy. This torus of dust and gas constitutes a reservoir of material that can fuel a violent episode of accretion activity and might be responsible for the star formation evidenced by the cluster of massive stars occupying the central parsec. Strong mid and far-infrared radiation emerges from the CND, so it is ideally suited for study by several instruments on SOFIA (see Morris et al 2005). The central several parsecs of the galaxy surrounding a massive black hole is a very special place in the galaxy. SOFIA with its broad range of instruments is the observatory of choice to address these questions. For example, high resolution spectroscopy using EXES, FIFI-LS,
GREAT, and CASIMIR will provide a powerful probe of the physical conditions (e.g., density and temperature), ionization state, energetics, mass, and kinematics of the gas through studies of the pure rotational $\text{H}_2$ lines, the atomic fine-structure lines of $[\text{OI}]$ (63 and 145$\mu$m), $[\text{OIII}]$ (52, 88$\mu$m), $[\text{OIV}]$ (25.9$\mu$m), $[\text{CII}]$ (158$\mu$m), $[\text{SiII}]$ (34$\mu$m), and $[\text{SI}]$ (26$\mu$m) and $[\text{SIII}]$ (18.7$\mu$m), and high level rotational levels of CO (e.g., $J = 14 - 13$).

4.7. Far-Infrared and Submillimeter Surveys

Using the first light heterodyne instruments, spectral line surveys can be made to reveal many new lines in the broad atmospheric window of SOFIA. With spectral line sensitivities similar to the CSO, many new lines should be observed for the first time. Using the far-infrared cameras, Galactic plane mapping will reveal structure never before observed at these wavelengths. Regions of high-mass and low-mass star formation can be imaged at 53, 88, 155, and 215$\mu$m at unprecedented spatial resolution.

5. Summary

The Stratospheric Observatory for Infrared Astronomy (SOFIA) will be the premier platform from which to make astronomical observations in the infrared and submillimeter range for the next twenty years. With the ability to deploy new and updated instruments, the observatory will play an important role in a variety of astrophysical problems well into the 21st century.

Acknowledgments

We would like to thank the entire SOFIA team for much tireless work on the SOFIA project. We would especially like to thank Tom Greene, Ted Dunham, Jim Elliot, Mark Morris, Rolf Güsten, John Lacy, Matt Richter, and Eli Dwek for putting together several of the science cases described in this paper.

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