The Stratospheric Observatory for Infrared Astronomy (SOFIA): Infrared Sensor Development and Science Capabilities

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ABSTRACT

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a unique airborne observatory designed to operate in the lower stratosphere to altitudes as high as 45,000 feet and above 99.8% of Earth's infrared-obscuring atmospheric water vapor. SOFIA's capabilities enable science that will complement and extend past, present and future infrared telescopes in wavelength range, angular and spectral resolution, and observing flexibility. The joint U.S. and German SOFIA project to develop and operate the 2.5-meter telescope aboard a Boeing 747-SP is now in its final stages of development. Flying in the stratosphere where the average atmospheric transmission is 80%, SOFIA allows observations throughout the infrared and submillimeter region of the spectrum. The SOFIA instrument complement includes broadband imagers, moderate resolution spectrographs capable of resolving broad spectral features due to dust and large molecules, and high resolution spectrometers suitable for kinematic studies of molecular and atomic gas lines.

A great strength of SOFIA is the enormous breadth of its capabilities and the flexibility with which those capabilities can be modified and improved to take advantage of advances in infrared technology. This paper and presentation will highlight the following points: A 2.5-meter effective-diameter optical-quality telescope for diffraction-limited imaging beyond 25 µm, giving the sharpest view of the sky provided by any current or developmental IR telescope operating in the 30-60 µm region; Wavelength coverage from 0.3 µm to 1.6 mm and high resolution spectroscopy (R to 10^5) at wavelengths between 5 and 150 µm; An 8 arcmin FOV allowing use of very large detector arrays; Ready observer access to science instruments which can be repaired in flight and changed between flights; A low-risk ability to incorporate new science-enabling instrument technologies and to create a whole "new" observatory several times during the lifetime of the facility; Opportunity for continuous training of instrumentalists to develop and test the next generation of instrumentation for both suborbital and space applications; Mobility, which allows access to the entire sky and a vastly increased number of stellar occultation events; Unique opportunities for educators and journalists to participate first-hand in exciting astronomical observations. This paper also describes the eight first generation science instruments and plans for future instrument development.

The mid- and far-IR wavelength regions are key to studying the dusty universe, typically hidden at shorter wavelengths. SOFIA science emphasizes the observatory's unique role to help understand star and planet formation, the interstellar medium, nearby galaxies and the galactic center, and our own solar system and other planetary systems. SOFIA's capabilities will enable a wide range of science investigations over its 20-year operational lifetime. SOFIA's first light flight is expected to occur in 2010 followed by a series of early science flights and instrument commissioning flights. SOFIA expects to declare limited operational capability in 2012, and full operational capability in 2014.

1. BACKGROUND

SOFIA is a unique airborne observatory utilizing a 2.5-meter infrared telescope on a modified Boeing 747-SP designed to operate in the lower stratosphere to altitudes as high as 45,000 feet and above 99.8% of Earth's obscuring atmospheric water vapor. A strength of SOFIA is the enormous breadth of its capabilities and the flexibility with which those capabilities can be modified and improved to take advantage of advances in infrared technology and extend past, present and future infrared telescopes in wavelength range, angular and spectral resolution, and observing flexibility not only for NASA science missions but SSA missions. SOFIA allows observations with multi-band infrared measurements throughout the infrared and submillimeter region beyond current ground-based capabilities. The SOFIA instrument complement includes broadband imagers and moderate resolution spectrographs. Current SOFIA sensors can access wavelength bands that are normally absorbed by the atmosphere from ground based telescopes. In addition, SOFIA offers an inexpensive, accessible alternative to space-based sensors while retaining many of the advantages including minimal atmospheric attenuation and dispersion.

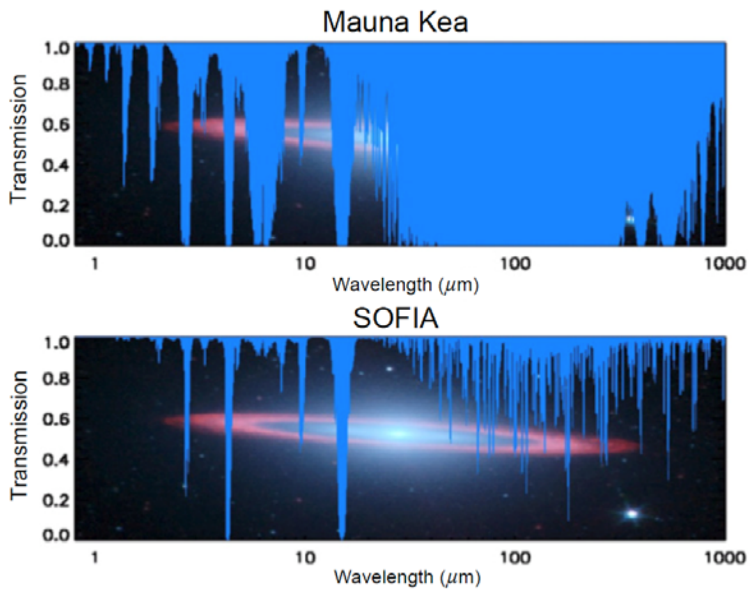

Fig. 1. The atmospheric transmission at SOFIA's operating altitude of ~45,000 feet compared to Mauna Kea.

A short list of SOFIA capabilities include:

- A 2.5-meter effective-diameter optical-quality telescope for diffraction-limited imaging beyond 25 μm, giving the sharpest view of the sky provided by any current or developmental IR telescope operating in the 30-60 μm region
- Wavelength coverage from 0.3 μm to 1.6 mm and high resolution spectroscopy (R to 10^5) at wavelengths between 5 and 150 μm
- An 8 arcmin FOV allowing use of very large detector arrays
- Ready observer access to sensors which can be serviced in flight and changed between flights
- A low-risk ability to incorporate new sensor technologies
- Opportunity for continuous training of instrumentalists to develop and test the next generation of instrumentation for both suborbital and space applications
- Mobility, which allows access to the entire sky and a vastly increased number of stellar occultation events
- Unique opportunities for educators to participate first-hand in exciting astronomical observations [5].

2. PLATFORM

SOFIA is built within a Boeing 747SP, modified to support and isolate the 45,000 pound telescope system on a balanced spherical hydraulic bearing installed in a pressure bulkhead aft of the wings (Fig. 3). The aft section of the aircraft was modified to include a sliding rigid and flexible door system that moves with an aerodynamic aperture mask in concert with the elevation motion of the telescope. Two factors motivated the aft installation of the telescope cavity instead of ahead of the wing of the aircraft. First, only a single forward pressure bulkhead was required. Second, the numerous flight control systems operating the wing did not have to be diverted. Infrared images of the exhaust plumes of NASA's 747 Shuttle Carrier in flight and numerical simulations show that heat and turbulence from the port engine exhaust plumes will not significantly degrade telescope performance [2] .

The SOFIA telescope, supplied by the German space agency DLR, was installed and tested in 2004. All major structural modifications to the aircraft were completed in early 2006 in Waco, Texas. The first test flights of the observatory began in April 2007 after which it was ferried to NASA's Dryden Flight Research Center in Palmdale, CA where further flight tests and development are being conducted. Closed door flight testing was completed in January, 2008. The first open door flight tests will begin in Fall 2009 with a first light instrument flight expected in 2010. At full operational capability in 2014, SOFIA will accommodate 50 science teams per year, selected through a rigorous proposal and review process.

The SOFIA Science and Mission Operations Center (SSMOC), located at NASA Ames Research Center, Moffett Field, CA, will oversee the mission operations and ensure the science productivity of the overall program. The platform itself and flight operations will be based out of NASA's Dryden Aircraft Operations Facility in Palmdale, CA. As part of the mission team, Universities Space Research Association (USRA) and the Deutsches SOFIA Institute (DSI) in Stutgart, Germany manage the science and mission operations for NASA/DLR.

Fig. 2. SOFIA with an F/A-18 safety chase during test flights.

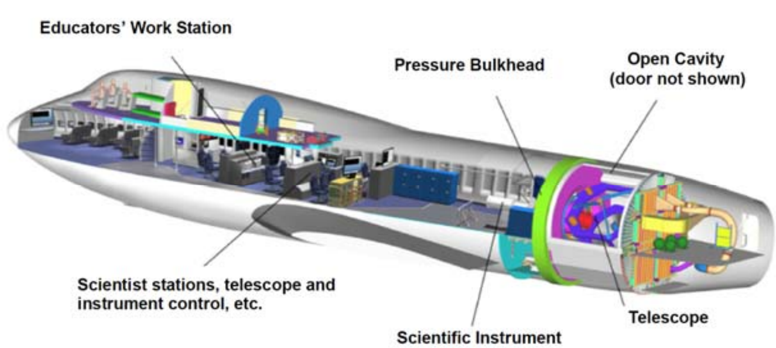

Fig. 3. SOFIA's internal layout optimized to accommodate the mission operations and science teams.

3. TELESCOPE

Designed by DLR, SOFIA's telescope is a bent Cassegrain with a 2.7m parabolic primary mirror (2.5m effective aperture) and a 0.35m hyperbolic secondary mirror. The telescope feeds two f/19.6 Nasmyth foci about 300 mm forward of the instrument flange: the IR focus for the instruments and a visible light focus for guiding. Beams are separated by a gold coated dichroic and an aluminum coated flat, M3-1 and M3-2 respectively, as shown in Fig. 4. The secondary mirror provides chop amplitudes of up to ±5 arcmin with adjustable frequency between 0 and 20 Hz. The visible beam is fed into the Focal Plane Imager (FPI), an optical focal plane guiding system. Independent of the FPI are two optical imaging and guiding cameras – a Fine Field Imager (FFI) and a Wide Field Imager (WFI). Both the FFI and WFI cameras are attached to the front ring of the telescope. These three guiding cameras represent increasingly large fields of view with decreasing pointing control accuracy [1].

The telescope is in an open cavity in the aft section of the aircraft (Fig. 3) and views the sky through a port-side doorway that is opened at flight altitude. The telescope is articulated by magnetic torquers around a spherical support bearing through which the Nasmyth beam is passed. The focal plane instruments and the observers are on the pressurized side of the 21-ft diameter pressure bulkhead on which the bearing is mounted, allowing a shirt-sleeve working environment for the researchers and crew. The telescope has an unvignetted elevation range of 20–60 degrees. The cross-elevation travel is only ±3 degrees, so the airplane must be steered to provide this telescope movement. Special flight plans must be developed to meet the needs of each observing program. Fig. 4. shows the bent Cassegrain-Nasmyth configuration [1].

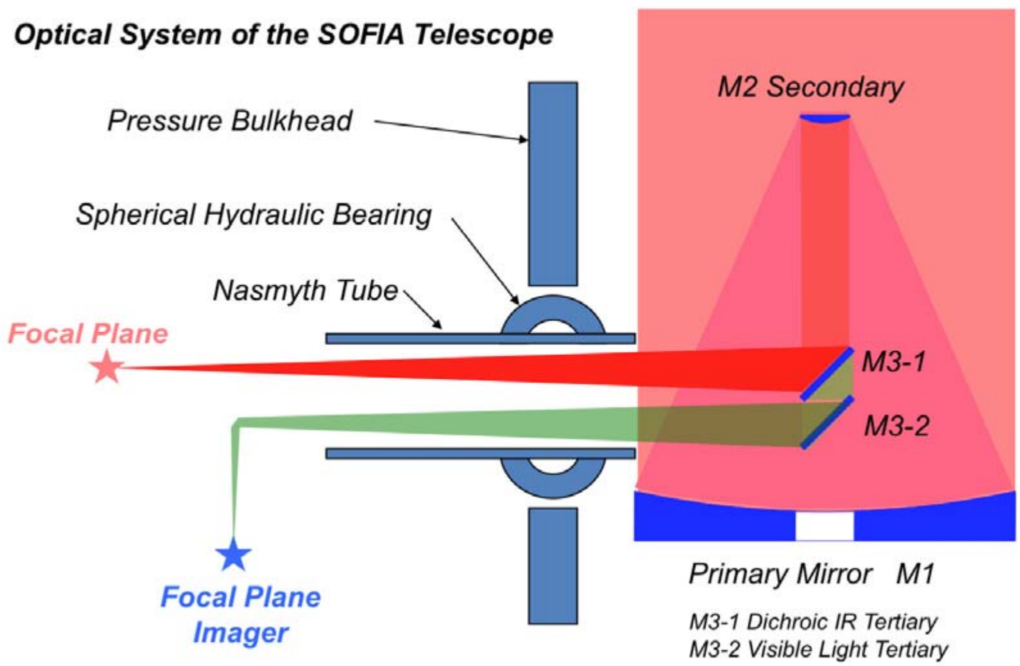

Fig. 4. SOFIA's bent Cassegrain-Nasmyth configuration [6].

SOFIA's telescope optics have been designed to provide 1.5 arcsec images on-axis (80% encircled energy at 0.6 μm) so that diffraction-limited performance can eventually be expected at wavelengths longer than 15 μm. Pointing stability of the telescope will be 1.0 arcsec RMS at first light and is expected to be improved to 0.2 arcsec RMS during the full operations phase that begins in 2014. A pointing accuracy of 0.5 arcsec will be achievable with on-axis focal plane tracking. Table 1 describes the Level 1 design and requirement specifications for SOFIA.

Table 1. SOFIA system characteristics [2].

Nominal Operational Wavelength	0.3 to 1600 μm	**Diffraction Limited Wavelengths**	$\geq$ 15 μm
Primary Mirror Diameter	2.7 meters	**Optical Configuration**	Bent Cassegrain with chopping secondary mirror and flat folding tertiary
System Clear Aperture Diameter	2.5 meters	**Chopper Frequencies**	1 to 20 Hz for 2-point square wave chop
Nominal System f-ratio	19.6	**Maximum Chop Throw on Sky**	+/- 4 arcmin (unvignetted)
Primary Mirror f-ratio	1.28	**Pointing Stability**	= 1.0" rms at first light = 0.2" rms in operations
Telescope's Unvignetted Elevation Range	20 to 60 degrees	**Pointing Accuracy**	= 0.5" with on-axis focal plane tracking
Unvignetted Field-of-View Diameter	8 arcmin	**Total Emissivity of Telescope (Goal)**	15% at 10 μm with dichroic tertiary 10% at 10 μm with aluminized tertiary
Image Quality of Telescope Optics at 0.6 μm	1.5 arcsec on-axis (80% encircled energy)	**Recovery Air Temperature in Cavity (and Optics Temperature)**	= 240 K
Diffraction Limited Image Size	0.1" • λ μm FWHM		

4. INSTRUMENTS

SOFIA is designed to accommodate a variety of instruments using light gathered from the telescope. Instruments can be changed out between flights to accommodate observers' requirements. The first generation of science instruments, built by participating research institutions, are in various stages of completion as indicated in Table 2. SOFIA will operate with three categories of instruments: 1) Facility instruments: general purpose, reliable and robust instruments that will be operated routinely and maintained by the SOFIA team in support of General Investigators (GI's), who will not be required to have extensive knowledge or experience in infrared instrumentation or observing techniques. Facility instruments remain at the SOFIA Science Operations Center in Palmdale where they will be maintained. 2) Principal Investigator-class science instruments: built and operated by Principal Investigator (PI) team members, both for their own research as well as for that of selected GI's. Normally the instrument will reside at the PI's institution, where all maintenance and upgrades will be accomplished. 3) Special purpose instruments: designed specifically for a particular observation or set of observations not possible or practical with facility or PI instruments. These instruments may incorporate technologies at the "edge-of-the-art" that would be too risky to include in a general purpose instrument. The following sections describe briefly the first generation SOFIA instruments. Instrument wavelength range and spectral resolution are summarized in Fig. 5.

4.1 FORCAST - Faint Object InfraRed CAmera for the SOFIA Telescope (Facility Instrument)

FORCAST is a mid-infrared diffraction-limited camera with selectable filters and two detectors for simultaneous imaging in the 4 - 25 μm and 25 - 40 μm spectral regions. FORCAST will also conduct low-resolution grism spectroscopy in the 4-8, 16-25 and/or 25-40 μm regions. The high-sensitivity widefield imaging uses 256x256 Si:As and Si:Sb detector arrays which sample at 0.75 arcsec/pixel giving a 3.2 arcmin x 3.2 arcmin field-of-view.

4.2 GREAT - German Receiver for Astronomy at Terahertz Frequencies (PI Instrument)

GREAT is a German-built 2-channel heterodyne spectrometer that offers observations in three frequency bands with frequency resolution as high as 45 kHz. The lower band, 1.4 - 1.9 THz, covers fine-structure lines of ionized nitrogen and carbon. The middle band is centered on the cosmologically relevant 1-0 transition of deuterated molecular hydrogen (HD) at 2.6 THz and the rotational ground-state transition of OH. A high-frequency band includes the 63 μm transition of [OI]. The receivers employ sensitive superconducting mixer elements, superconductor-insulator-superconductor (SIS) tunnel junctions and hot electron bolometers. A polarizing beam splitter allows simultaneous measurements of two channels at the same time.

4.3 FIFI LS - Field Imaging Far-Infrared Line Spectrometer (PI Instrument)

FIFI LS is a German-built integral field spectrometer, containing two medium resolution (R~1700) grating spectrometers with common foreoptics feeding two 16 x 25 pixel Ge:Ga detector arrays. A beamsplitter allows the two Littrow spectrometers to observe an object simultaneously in two spectral lines in the wavelength ranges 42 - 110 μm, and 110 - 210 μm. An image slicer in each spectrometer redistributes 5 x 5 pixel diffraction-limited spatial fields-of-view along 25 entrance slits. FIFI LS will offer spectral resolution of 170 km/s resolution over a velocity range of ~1500 to 3000 km/s around selected lines for each of the 25 spatial pixels.

4.4 FLITECAM - First Light Infrared Test Experiment CAMera (Facility Instrument)

FLITECAM will provide seeing-limited imaging from 1-3 μm and diffraction-limited imaging from 3 to 5.2 μm. Its objective is to cover near infrared science applications taking advantage of good atmospheric transmission and low thermal background. FLITECAM will also provide moderate resolution grism spectroscopy (R~2000).

4.5 CASIMIR - CAltech Submillimeter Interstellar Medium Investigations Receiver (PI Instrument)

CASIMIR is a submillimeter and far-infrared heterodyne receiver that uses sensitive superconducting mixers, including both tunnel junction superconductor-insulator-superconductor (SIS) devices and eventually hot electron bolometers (HEB). The local oscillators are continuously tunable. CASIMIR will cover the 500-2100 GHz frequency range in seven bands: SIS mixers in four bands up to 1200 GHz, and HEB mixers in three bands covering the rest. Four bands can be selected for use on a given flight. The receiver has an intermediate-frequency (IF) bandwidth of 4 GHz, processed by a high-resolution backend commercial Fast Fourier Transform (FFT) spectrometer with 250 kHz resolution.

4.6 HAWC - High-resolution Airborne Wideband Camera (Facility Instrument)

HAWC is a far-infrared camera designed to cover the 40-300 μm spectral range at diffraction-limited resolution. HAWC utilizes a 12x32 pixel array of bolometer detectors constructed using the silicon pop-up detector (SPUD) technology developed at NASA's Goddard Space Flight Center. The array is cooled by an adiabatic demagnetization refrigerator and operated at a temperature of 0.2 K. HAWC may eventually be upgraded to perform far infrared polarimetry.

4.7 EXES - Echelon-Cross-Echelle Spectrograph (PI Instrument)

The Echelon-Cross-Echelle Spectrograph (EXES) operates in three spectroscopic modes (R~10^5, 10^4, and 3000) from 5-28 μm using a 1024 x 1024 Si:As blocked impurity band (BIB) detector. High dispersion is provided by a large echelon grating. This requires an echelle grating to cross-disperse the spectrum, resulting in continuous wavelength coverage of ~5 cm^{-1} and a slit length of ~10" at R=10^5. The echelon can be bypassed so that either the echelle or low order grating can act as the sole dispersive element.

4.8 HIPO - High-speed Imaging Photometer for Occultation (Special Purpose Instrument)

HIPO is a special-purpose instrument designed to provide simultaneous highspeed, time-resolved imaging photometry at two optical wavelengths. HIPO makes use of SOFIA's mobility, freedom from clouds, and near-absence of scintillation noise to provide data on transient events like stellar occultations and data acquisition at optical and near-IR wavelengths. HIPO and FLITECAM can be mounted simultaneously.

Table 2 – SOFIA first generation instruments [3].

SOFIA Instrument	Description	Built by / PI	λ range (μm) spec res ($\lambda/\Delta\lambda$)	Field of View Array Size	Available
FORCAST	Faint Object InfraRed CAmera for the SOFIA Telescope Facility Instrument - Mid IR Camera and Grism Spectrometer	Cornell T. Herter	5 - 40 R ~ 200	3.2' x 3.2' 256 x 256 Si:As, Si:Sb	2010
GREAT	German Receiver for Astronomy at Terahertz Frequencies PI Instrument - Heterodyne Spectrometer	MPIfR, KOSMA DLR-WS R. Güsten	60 - 200 $R = 10^6 - 10^8$	Diffraction Limited Single pixel heterodyne	2010
FIFI LS	Field Imaging Far-Infrared Line Spectrometer PI Instrument w/ facility-like capabilities - Imaging Grating Spectrometer	MPE, Garching A. Poglitsch	42 - 210 R = 1000 - 3750	30"x30" (Blue) 60"x60" (Red) 2 - 16x5x5 Ge:Ga	2010
HIPO	High-speed Imaging Photometer for Occultation Special PI Instrument	Lowell Obs. E. Dunham	.3 - 1.1	5.6' x 5.6' 1024x1024 CCD	2012
FLITECAM	First Light Infrared Test Experiment CAMera Facility Instrument - Near IR Test Camera and Grism Spectrometer	UCLA I. McLean	1 - 5 R~2000	8.2' x 8.2' 1024x1024 InSb	2012
CASIMIR	CAltech Submillimeter Interstellar Medium Investigations Receiver PI Instrument - Heterodyne Spectrometer	Caltech J. Zmuidzinas	200 - 600 $R = 3x10^4 - 6x10^6$	Diffraction Limited Single pixel heterodyne	2012
HAWC	High-resolution Airborne Wideband Camera Facility Instrument - Far Infrared Bolometer Camera	Univ of Chicago D. Harper	50 - 240	Diffraction Limited 12x32 Bolometer	2013
EXES	Echelon-Cross-Echelle Spectrograph PI Instrument - Echelon Spectrometer	UT/UC Davis NASA Ames M. Richter	5 - 28 $R = 10^5$, 10^4, or 3000	5" to 90" slit 1024x1024 Si:As	2013

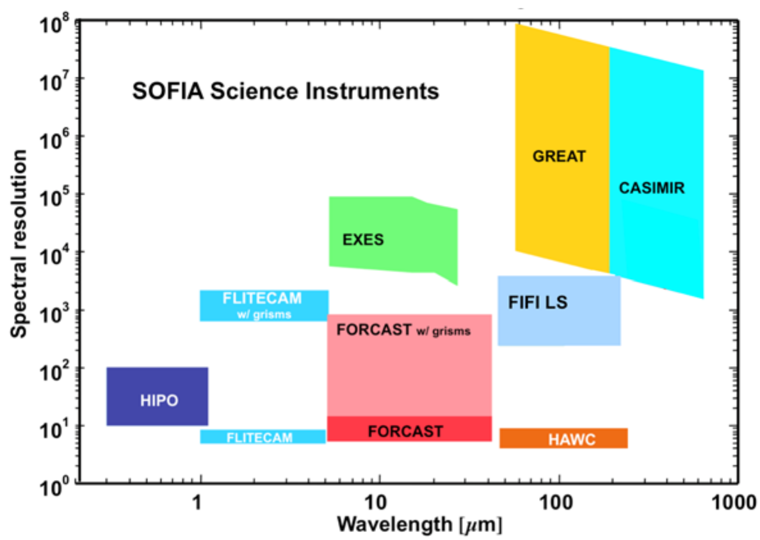

Figure 5. Performance parameters of SOFIA's first generation of instruments

5. SCIENCE

The SOFIA observatory is open to the entire international astronomical community. Observing time is awarded based on peer review of proposals submitted in response to regular calls. Researchers will be granted observing time in units of science flight hours, not full flights. When fully operational, SOFIA plans to provide ~960 hours of science observing time each year. The next call for science proposals is expected in late 2009 [6].

The breadth of scientific investigations made possible by SOFIA's large suite of science instruments and broad wavelength coverage is enormous. Many of the most interesting objects in the universe, such as black holes and newly forming stars and planetary systems, are hidden from view by dense layers of obscuring dust and gas. Information about these objects and their astrophysical context must be gleaned from their interaction with their environment. In essence, the obscuring dust and gas absorb the energetic photons from embedded objects and convert them into IR and sub-millimeter radiation. SOFIA, with its diverse complement of instruments, is uniquely suited to study deeply embedded objects and to determine their role in the evolution of galaxies.

5.1 The Formation of Stars and Planets

SOFIA will provide vital information on the physical, chemical, and dynamical processes at work in the formation of planets and stars of all masses. The process of massive star formation remains largely unknown despite recent progress in the observation and theory of low mass star formation. SOFIA will collect comprehensive data on hundreds of massive stars to help understand how these stars form in different environments. In support of our understanding of planetary formation, SOFIA will observe circumstellar disks around young stars, the environment in which planets form. SOFIA data will be used to refine accretion and cooling models of these disks, and to study the kinematics, composition, and evolution of disks around low-mass young stellar objects. The study of exo-planetary systems and their formation is one of the fastest growing topics in astronomy. SOFIA data can help to trace our chemical origins and will contribute to the study of the chemical composition and modification of the gaseous and solid-state material in dense protostellar and protoplanetary environments.

5.2 The Interstellar Medium of the Milky Way

The interstellar medium (ISM) contains an elemental record of the history of the galaxy. SOFIA will gather high resolution spectra that probe the physics and chemistry of the birth and death of stars. SOFIA will explore 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). PAH molecules are can be used to trace the chemistry of prebiotic molecules within the shrouded nurseries where stars and planetary systems form. Stellar radiation from massive stars transforms the nearby environment driving the chemistry of star forming regions. SOFIA will measure changing physical conditions, such as density, metallicity, and temperature in these regions. Dust, an important component of the ISM and the clouds from which stars form, can provide effective shielding from harsh interstellar radiation. The chemistry and composition of the dust grains, as well as that of the ISM gas, determines how interstellar ices form. Thermal and radiative processing of these simple ices yields the complex chemistry that finds its way into planetary systems and eventually into living beings. Understanding the chemistry of interstellar dust and the environments where dust survives will thus provide important clues about the chemistry of life.

5.3 Galaxies and the Galactic Center

Understanding of the star-formation history of galaxies beyond our own Milky Way is a key challenge for observational astrophysics. The physical conditions of the ISM and the stellar radiation field properties within these galaxies can be probed using far-infrared fine structure lines. SOFIA observations of the central molecular zone of our own galaxy will provide critical, spatially resolved information about how the activity there is produced by the interactions of stars, powerful gas flows and stellar winds, strong magnetic fields, and the supermassive black hole. The abundant energy of galactic nuclei emerges almost entirely in the infrared, and is well suited for study by SOFIA. SOFIA's unrivaled far-infrared mapping capabilities will allow investigations of the ISM in nearby galaxies at spatial resolution sufficient to resolve spiral arms and to distinguish large star formation regions.

5.4 Planetary Science

Infrared observations of comets, near-Earth asteroids, moons, and planets reveal evidence of their origin and the origin of our Solar System. The existence of water and organic materials in primitive bodies offers clues as to where and how these bodies formed. SOFIA offers the unique capability, relative to space- or ground-based infrared observatories, to observe objects closer to the Sun than the Earth: for example, comets in their most active phases, and the planet Venus. SOFIA will test new dynamic mixing models for the early solar systems by tracking the isotopic composition of water, mineralogy, and organic content of comets. SOFIA can point directly at bright planets and their moons, and observe spectral features of water and organic molecules, measurements that have to date eluded space based missions. SOFIA's broadband, high resolution spectroscopy will enable studies of many molecules predicted by theory in the atmospheres of Venus and Titan, and the kinematics of Venusian winds. SOFIA's spectroscopy will also enable investigation of the global chemical inventory of the gas giants, with especially good spatial resolution for Jupiter and Saturn. SOFIA will observe stellar occultations by Trans-Neptunian Objects and other transient events from optimum locations anywhere on Earth. SOFIA will also be able to monitor seasonal and episodic changes in slow-orbiting outer planets over decade timescales.

6. NEW INSTRUMENT DEVELOPMENT

A major advantage SOFIA offers over space-based missions is the ability to rapidly incorporate instrument improvements and to accommodate upgrades in response to new technology. SOFIA is an ideal platform for the first or early deployment of new detector and instrumentation technology. SOFIA instruments can be more complex and larger in volume, weight and power consumption than those deployed on space-based observatories. Focal plane technology is expanding rapidly in the far-IR, and major advances in detector sensitivity and array size are anticipated. Unlike typical space-borne observatories, SOFIA will be able to incorporate and test the latest state-of-the-art technology in terms of sensitivity, detector response time, observation technique, and spectral resolution [4].

NASA plans to support new instrument development and issue a call for new instruments in FY 2011. Additional calls every 3 years are expected to result in one new instrument or major upgrade to observatory instrumentation each year. Recent evaluations of the scientific case for SOFIA have stressed the importance of imaging and spectroscopic polarization measurements for a number of key investigations. Suggestions for future instrumentation include:

- Expanded heterodyne wavelength coverage
- Arrays of heterodyne detectors
- Polarimeters
- Moderate resolution integral field unit spectrometer (5 to 60 μm)
- Low resolution scanning spectrometer (5 to 100 μm)
- High resolution spectrometer (1-5 μm, 28-100 μm)
- Kinetic Induction Detector (KID) Spectrometer

7. SUMMARY

The SOFIA Observatory offers key advantages that make it a unique tool for astronomy in the coming decades:

• SOFIA is a near-space observatory that comes home after every flight. SOFIA's scientific instruments can be exchanged regularly to accommodate changing science requirements and new technologies. SOFIA instruments do not need to be space qualified, and the observatory can accommodate, large, massive, complex and sophisticated instruments with substantial power and heat dissipation needs. Simple adjustments or repairs can be performed on an instrument in flight, further increasing SOFIA's flexibility and science productivity. And SOFIA is an ideal platform for the first or early deployment of new detector and instrumentation technologies.

• SOFIA has unique capabilities for studying transient events. The observatory can operate from airbases worldwide on short notice to respond to new discoveries in both the northern and southern hemispheres. SOFIA has the flexibility to respond to events such as supernovae and nova explosions, cometary impacts, comet apparitions, eclipses, occultations, near-Earth object observing opportunities, activity in Active Galactic Nuclei, and activity in luminous variable stars.

• SOFIA's wide range of instruments will facilitate a coordinated science program through analysis of specific targets. No other observatory operating in SOFIA's wavelength range offers such a large variety of available instruments over a long period of time. SOFIA will be able to make observations that are not possible for many space observatories because of the viewing constraints imposed by their orbits. For example, SOFIA can observe astrophysical events that occur close to the sun. SOFIA will be the only infrared mission allowing observations of the inner planets and comets when they are brightest and most active.

• SOFIA's 20-year operational lifetime will enable long-term temporal studies and follow-up of work initiated by SOFIA itself and by other observatories. Many space missions are relatively short compared with the critical cycle of observation, analysis, and further observation. The Herschel and James Webb Space Telescope (JWST) Observatories will raise scientific questions that will benefit from follow-up observations well after their missions have ended. On the basis of present plans, SOFIA will be the only facility operating between 25 and 350 μm following Herschel and JWST. SOFIA will keep the community engaged in fundamental science research until the next generation of missions is launched.

• SOFIA presents an ideal venue in which to educate students, where they can participate in hands-on, cutting-edge space technology developments. The continuous training of instrumentalists (students and faculty) is a high priority in the astronomy community. These opportunities are generally not available to students working on satellite projects. SOFIA will energize the next generation of young experimental astrophysicists and help to develop their talents in many different scientific and engineering areas. SOFIA graduate and post-doctoral students will form a rich reservoir of talent and will become the next generation of Principal Investigators and Instrument Scientists.

• Because of its accessibility and ability to carry passengers, SOFIA will include a vigorous, highly visible Education and Public Outreach (E&PO) program designed to exploit the unique and inspirational attributes of airborne astronomy. SOFIA is the only major research observatory designed to bring nonscientists into routine close contact with scientists in a research environment.

8. ACKNOWLEDGEMENTS

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