SOFIA: An Observatory for THz Science and Technology

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ABSTRACT

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is the next generation of airborne astronomical observatories. Funded by the U.S. and German space agencies with an expected operational lifetime of 20 years, SOFIA is scheduled for science flights beginning in late-2009. The observatory consists of a 747-SP aircraft modified to accommodate a 2.5-meter infrared telescope within an open port cavity. Academic and government laboratories spanning both the U.S. and Germany are developing science instruments for SOFIA. With an evolving suite of state-of-the-art technologies, SOFIA will explore the emission of astronomical sources with an unprecedented level of angular resolution (θ[arc-seconds] = 0.1 x wavelength [μm]) and spectral line sensitivity over a core frequency range of 1 – 10 THz (i.e. wavelengths of 30 – 300 microns). On April 26, 2007, the first test flight of the heavily modified SOFIA aircraft was achieved in Waco, Texas. The current status of SOFIA is available from the observatory web site at http://sofia.arc.nasa.gov and is updated frequently.

Keywords: SOFIA, airborne astronomy, far-infrared, instruments

1. INTRODUCTION

The Stratospheric Observatory For Infrared Astronomy (SOFIA) along with the Spitzer and Herschel observatories are the U.S. and European premier astronomical programs for infrared and submillimeter astronomy. SOFIA, a joint project of NASA and the German Space Agency (DLR) is a 2.5-meter telescope in a Boeing 747-SP aircraft designed to make sensitive infrared measurements of a wide range of astronomical objects (Erickson and Davidson 1995, Becklin 1997, Casey 2004). It will fly at and above 12.5 km, where the telescope will collect radiation in the wavelength range of 0.3 μm to 1.6 mm. The SOFIA science program 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. In Germany, the University of Stuttgart has been awarded the contract to run the Deutsches SOFIA Institut (DSI). Science communities in the U.S. and Germany have the responsibilities for the development of the science instruments to be installed on the SOFIA telescope. In the U.S., science instrument teams are selected and funded through an a peer review and ranking of the proposals received.

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 NASA's Dryden Flight Research Center in Edwards, California, but occasionally from other bases around the world, especially in the Southern Hemisphere. SOFIA will fly above 12.5 km, where the typical precipitable water

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column depth is less than 10 µm. A graphic comparison of the typical transmission at mountaintop and aircraft altitudes 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 atmosphere at aircraft altitudes is mostly transparent at infrared and submillimeter wavelengths. In particular, THz frequencies (30 – 300 microns) are strongly blocked at typical Mauna Kea-type water vapor values (ZH2O ~ 1 mm).

The SOFIA Science and Mission Operations Center (SSMOC) will be located at NASA's Ames Research Center in Moffett Field, CA and is currently operated by USRA under contract to NASA. The SOFIA Program expects to support approximately 50 investigation teams per year through a peer reviewed proposal process.

In early-1997, NASA acquired the SOFIA aircraft, the 'Clipper Lindbergh', from United Airlines. The telescope and support structure was developed by DLR and delivered to NASA in late-2002. The first ground-based observations with the SOFIA telescope were in mid-2004. The first flight of the modified aircraft was on April 26, 2007 and is shown in Figure 2. With most U.S. and German science instruments nearing completion, the first science flights are expected in early-2009.

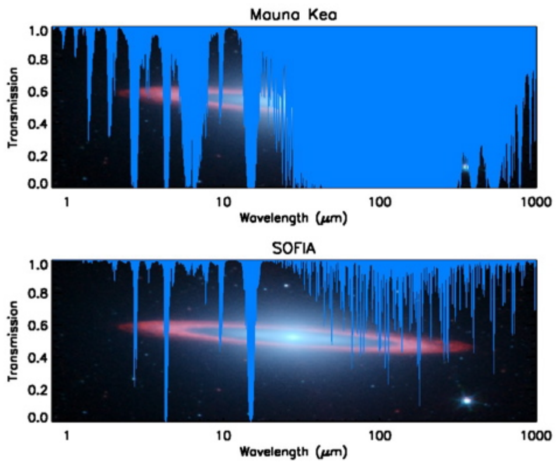

Figure 1. The comparison of atmospheric transmission at THz frequencies between ground based and airborne facilities. Note that THz observations (1 – 10 THz) are completely blocked by the effects of atmospheric water vapor.

Figure 2. The first test flight of the SOFIA aircraft occurred on April 26, 2007 in Waco, Texas after nearly ten years of development. Open door test flight are expected in 2008 with science flights beginning in 2009.

3. SOFIA'S TELESCOPE AND FIRST GENERATION INSTRUMENTS

Mounted in the aft section of the aircraft, the SOFIA telescope is stabilized in-flight by a three-axis gyroscope package coupled to a magneto-torque motor drive via a tuned servo-system. Guide camera and strain gauges provide low frequency corrections for close-loop tracking on celestial sources. The primary mirror is finished to provide quality images at optical wavelengths. The portside telescope cavity door is typically closed for take-off and landings so as the keep the aluminized mirror surface as clean as possible (and of moderately low emissivity). The door is opened at altitude and is articulated to track the telescope's range of motion in elevation (20 – 60 degrees). A secondary mirror drive provides both chopping and scanning motions. The top-level characteristics for SOFIA are listed in Table 1.

Table 1. SOFIA Characteristics

Nominal Operational Wavelength Range	0.3 to 1600 microns
Primary Mirror Diameter	2.7 meters
System Clear Aperture Diameter	2.5 meters
Nominal System f-ratio	19.6
Primary Mirror f-ratio	1.28
Telescope's Unvignetted Elevation Range	20 – 60 degrees
Unvignetted Field-of-view Diameter	8 arc-minutes, 13 arc-minutes at optimum focus
Maximum Chop Throw on Sky	± 4 arc minutes (unvignetted)
Diffraction-Limited Wavelengths	> 15 microns
Recovery Air and Optical Temperature in Cavity	240 K
Image Quality of Telescope Optics (at 0.6 microns)	1.0" on-axis (80% encircled energy)
Optical Configuration	Bent Cassegrain, chopping secondary and flat folding tertiary
Chopper Frequencies	1 to 20 Hertz for 2-point square-wave chop
Pointing Stability	< 2.0" rms for first-light
Pointing Accuracy	= 0.5" if on-axis Focal Plane tracking = 3" if on-axis Fine-Field tracking
Total Emissivity of Telescope (goal)	15% at 10 microns with dichroic tertiary 10% at 10 microns with aluminized tertiary
Chopped Image Quality due to coma for ± 4' chop throw	= 9.1" for 80% encircled energy diameter = 5.8" for 50% encircled energy diameter

A total of nine instruments have been selected and are now under development. SOFIA's 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 spectrometers geared towards studies of broad dust and molecular features, to high resolution instruments capable of velocity-resolved gas phase line studies. The discovery space of SOFIA's first generation instrument suite is illustrated in Figure 3.

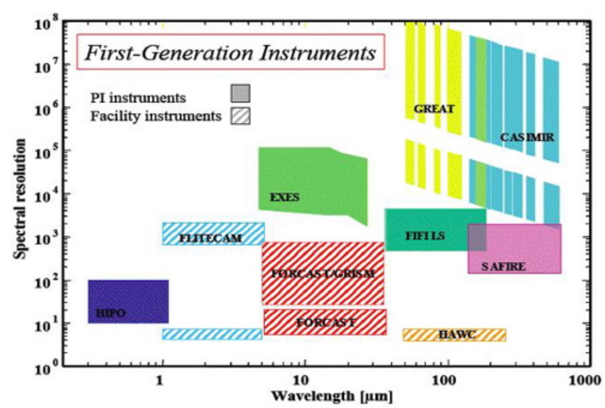

Figure 3. The phase space of wavelength coverage versus spectral resolution for SOFIA's first generation instrument suite. The instruments GREAT, CASIMIR, and SAFIRE are discussed in this symposium.

The operational parameters of the first generation instruments are listed in Table 2 below. SOFIA science instruments are either principal investigator class or facility class. In particular, the current suite includes three Facility Class Science Instruments (FSI): HAWC, FORCAST, and FLITECAM. Facility class instruments are 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 teams. Two of the PI Class instruments (FIFI-ls and GREAT) are being developed in Germany.

Table 2: SOFIA First Light Instruments

PI	Institution	Name	Type of instrument
E. Dunham	Lowell Observatory	HIPO	High-speed Imaging Photometer for Occultations 0.3-1.1 µm
I. McLean	UCLA	FLITECAM	Near-IR Camera 1-5 µm; GRISM $R = 2{,}000$
J. Lacy	Univ. of Texas	EXES	Echelon spectrometer 5-28µm; $R = 10^5$, 10^4, or 3,000
T. Herter	Cornell Univ.	FORCAST	Mid IR Camera 5-40 µm
D. A. Harper	Univ. of Chicago	HAWC	Far IR Bolometer Camera 50-240 µm
A. Poglitsch	MPE, Garching	FIFI-LS	Field Imaging Far IR Line Spectrometer 4-210 µm; $R \cong 2{,}000$
S. Moseley	NASA GSFC	SAFIRE	Imaging Fabry-Perot Bolometer Array Spectrometer 145-655 µm; $R = 1{,}000$-$2{,}000$
R. Güsten	MPIfR, KOSMA	GREAT	Heterodyne Spectrometer 60-200 µm $R = 10^4$-10^8
J. Zmuidzinas	Caltech	CASIMIR	Heterodyne Spectrometer 200-600 µm $R = 10^4$-10^8

An obvious 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 "home" (the 3 to 150 µm range) of many of the important atomic and ionic fine structure lines as well as ro-vibrational transitions of many simple molecules, including H_2O, CH_4, and C_2H_2.

However, a great strength of an airborne astronomy program is that science instruments can be regularly exchanged between flight opportunities. In addition, compared to space-based missions, much larger and more massive instruments can be flown. Likewise, mission constraints such as heat dissipation or power consumption are of less concern for airborne platforms than for satellites. The SOFIA instrument program takes full advantage of these differences. SOFIA's first generation instrumentation is technically very diverse.[1]

Another advantage of an airborne observatory, as compared to a space-based mission, is the ability to rapidly incorporate improvements in technology and other instrument upgrades. In this way, instrumentation can quickly react to the latest technological innovations. At frequencies of 1 – 10 THz (30 – 300 microns), technology is still rapidly improving and major advances in detector sensitivity and array size can be expected over SOFIA's 20-year lifetime. The SOFIA program plans to support a technology development and new instrumentation program that will essentially provide an entirely new instrument complement (and thus an entirely new mission) every ~10 years. Given the cost of new space-based instrumentation and the

[1] Details on all SOFIA science instrument are available from: http://www.sofia.arc.nasa.gov/Science/instruments/sci_instruments.html .

rapidly evolving capability at THz frequencies, a modest level of funding for new SOFIA instruments expects to yield a bountiful science return to NASA, DLR, and the at-large astronomical community.

4. THZ SCIENCE WITH SOFIA

As illustrated in Figure 4, 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 they tell 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 THz science that may be done with SOFIA.

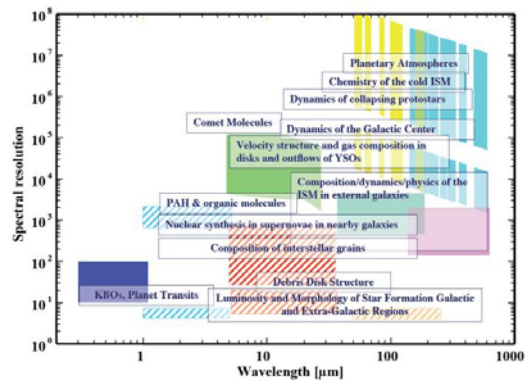

Figure 4. An overlay of SOFIA science with the phase space of the observatory's first generation instrument suite.

4.1. The ISM 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.

Of specific importance are the atomic fine structure lines of [OI] at 63 and 145 μm and of [CII] at 158μm. 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.

4.2. 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 μm) 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 astration by nuclear burning in stars throughout the galaxy. SOFIA is the only observatory with the appropriate wavelength coverage and spectral resolution required for this study (see Güsten 2005).

4.3. THz (Far-Infared and Submillimeter) Surveys

Following the spectral studies of ISO (e.g. van Dishoeck and Tielens, 2001) and Spitzer (e.g. Watson et al, 2004), and in line with the spectral surveys proposed for Herschel (e.g. Schilke et al, 1997), SOFIA will likely also develop its own spectral surveys program. Using the first light heterodyne instruments, spectral line surveys can be made to reveal many new lines in the broad atmospheric window of SOFIA not covered by Herschel. With spectral line sensitivities similar to the CSO, many new lines should be observed for the first time in the 1.3 - 1.5 THz region and the 2 - 5 THz region

5. SUMMARY

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

6. ACKNOWLEDGMENTS

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7. REFERENCES

Becklin, E. E., "The Stratospheric Observatory for Infrared Astronomy (SOFIA)", in the *Proceedings of the ESA Symposium "The Far Infrared And Submillimetre Universe"*, pp. 201-206, ESA SP-401, Grenoble, France, August 1997.

Casey, S. C., "The SOFIA program: astronomers return to the stratosphere", in *Advances in Space Research*, p 560 – 567, 34, 2004.

Erickson, E. F. and Davidson, J. A., "SOFIA: The Future of Airborne Astronomy", in *Proceedings of the Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust*, edited by M. R. Haas, J. A. Davidson, and E. F. Erickson, vol. 73, Astronomical Society of the Pacific, San Francisco, CA, 1995.

Güsten, R., The Interstellar Deuterium Abundance, *http://www.sofia.usra.edu/Science/science_cases/index.html*, 2005.

Schilke, P., Phillips, T. G., and Mehringer, D. M. First Wide Band Submillimeter Line Surveys, in: Wilson, A. (Ed.), The Far Infrared and Submillimeter Universe, pp. 73-80, (1997).

van Dishoeck, E. F. and Tielens, A. G. G. M. Space-borne Observations of the Life Cycle of Interstellar Gas and Dust, in: Bleeker, J. A. M., Geiss, J., and Huber, M. C. E. (Eds.), The Century of Space Science, pp. 607-646, 2001.

Watson, D. M. et al. Mid-infrared spectra of class I protostars in Taurus. Astrophys. J. Supplement Series 154, 391-395, 2004.