The Stratospheric Observatory SOFIA

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Abstract – The Stratospheric Observatory For Infrared Astronomy (SOFIA) is a joint US-German project and it will be the premier observatory for infrared and submillimeter astronomy for the coming 20 years of operation. A Boeing 747-SP aircraft will carry a 2.7 m telescope designed to make sensitive measurements of a wide range of objects. It will fly above 12.5 km for as long as 7-9 hours, where the telescope collects radiation in the wavelength range from 300 nm to 1.6 mm region of the electromagnetic spectrum. The telescope will be combined with several instruments provided by the US and German sides, which will cover facility-class science instruments as well as principle investigator-class instruments – cameras, imaging spectrometers and heterodyne spectrometers – covering the entire available wavelength range. The expected performance of the telescope and instruments is described within this paper.

1. INTRODUCTION

SOFIA the next generation airborne astronomical observatory is nearly completed. Already this year the first instruments for SOFIA will see the first light. The way to realize the airborne observatory was long and many technical solutions had to be found in the past. Beside astronomical observations SOFIA might open new challenges for atmospheric investigations – remote sensing and in-situ – like determination of water vapor variability and particle concentration in the stratosphere as well as the composition of UV radiation. In addition SOFIA could be used for calibration and validation of satellite data sets.

Keywords: Infrared astronomy, airborne telescope

2. THE AIRBORNE OBSERVATORY

Fig. 1 shows an in-flight rendition of the Boeing 747SP SOFIA aircraft and the telescope. This aircraft model was chosen for its wide fuselage allowing for the installation of the telescope, and for its flight performance, allowing for observations from altitudes up to 13.7 km (45,000 ft). The major modifications of the aircraft required in order to transform it into an astronomical observatory were the creation of a telescope cavity, the cutting of the fuselage opening for the telescope to look out, the fuselage modification for structural integrity, stability and control of the airflow, and the conversion of the passenger cabin into a control room.

Fig. 2 shows a cut-away view through the aircraft. The telescope is located in a cavity in the rear, which is sealed off from the pressurized, warm cabin area in the front by a bulkhead wall. The bulkhead wall supports all the weight of the telescope. The telescope drive system, counterweights, most of the Nasmyth tube and the science instruments are located within the cabin and are accessible during flight. Access to the cavity is provided through a door in the aft section when the aircraft is on the ground. This section also contains the devices for precooling the telescope prior to each observation flight and floating the cavity with dry N_2 during warming up after the flight.

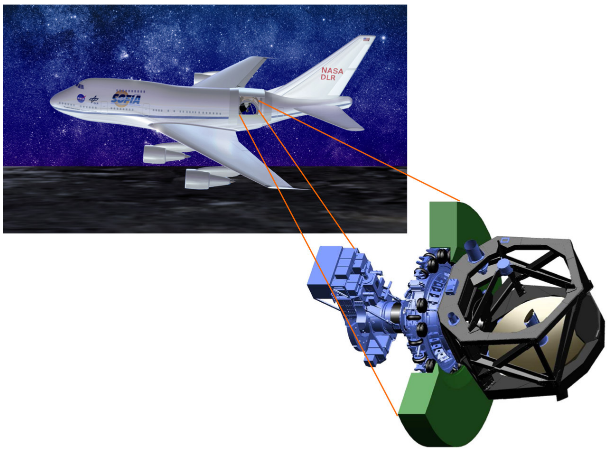

Figure 1. SOFIA and its telescope.

The cavity is sealed from the outside by a slightly recessed barrel door. The door opens as soon as the cruising altitude has been reached, but keeps the opening as small as possible. Wind tunnel tests have shown that an optimized outer shape of the door can more or less maintain the laminar airflow across the hole. However, some turbulent wind loads on the telescope structure will still remain. These wind loads will be compensated for by the telescope drive system.

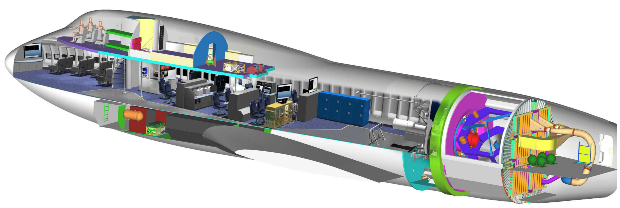

Figure 2. Cut-away view into the SOFIA aircraft

For balancing reasons, most of the heavy telescope control electronics, power supplies and heat exchanger are located in the front of the aircraft. The observers and the telescope operation crew are located in the section between the wings. If any space is left over, a small conference table plus seats will be provided. On the first and second floor some space will be reserved for visitors.

The telescope is separated mechanically from the aircraft by a system of vibration isolators located between the bulkhead and the bearing. These isolators passively protect the telescope from aircraft vibrations by dampening. Within this isolated reference

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frame, the telescope is actively pointed and stabilized by a 'coarse drive system' (which allows telescope movement in elevation between 15° and 70°) and a 'fine drive torque motor' arranged in segments around the spherical bearing (for telescope elevation motion within ±3°). The fine drive system can move the telescope in cross-elevation and the line-of-sight axis by ±3°. Telescope pointing outside this range is done by choice of the flight trajectory, e.g. flying West for objects in the South, of flying East for objects in the North. Target acquisition and tracking uses three laser gyros for reference and three cameras, i.e. a wide field, a fine field and a focal plane imager with a 6°, 70 arcmin and 8 arcmin field-of-view, respectively. A detailed description of the SOFIA telescope and its subsystems can be found in (Airborne Telescope Systems, 2000) and (Airborne Telescope Systems II, 2002).

Achieving highly precise pointing stability of the telescope onboard the aircraft is indeed one of the major challenges of the project. Residual vibrations from the aircraft and wind loads on the telescope in the open port compartment need to be compensated. In addition, these two external disturbances will introduce bending of the telescope structure that needs to be corrected as well. The system is so complex, that a special 'modal survey test' will be conducted after the telescope and its support structures are finally assembled in their flight configuration. The results of this test will be used to 'train' the pointing control system on how to react to the different disturbances the telescope might experience in flight. Finally, the actuated secondary mirror might be used for the finest level of image stabilization, to reach the specified value of 0.2 arcsec (RMS). But use of the secondary mirror for image stabilization must be kept to a minimum (< 1 arcsec corrections) because of the unwanted infrared background variations introduced by such a method.

3. SOFIA SCIENCE INSTRUMENTS

Nine scientific instruments for the reception and analysis of the light collected by the SOFIA telescope are currently under development, seven by astronomical institutions in the U.S. and two by institutes in Germany. Table 1 shows the type of the instruments and where they are being built. There are three categories or instrument types, defining basically their modes of operation. Facility science instruments are designed to be versatile using established technology for broad community use. General observers will work with the observatory's science staff to prepare their proposals, plan and conduct their observations, and to reduce their data. The SOFIA facility instrument program is assisted by the development of a data cycle system, including pipeline processing and archiving of data. Principal investigator (PI) instruments are not formally delivered to the observatory. Instead, the PI-team remains in charge of operating and maintaining their instruments and will visit the observatory with a group of personnel needed to conduct observing flights. The teams are flexible to update their instruments to the most recent and best technologies, e.g. the most sensitive detectors, within the regulations of flight certification. Specialty science instruments are developed and operated like PI-instruments but are focused on a specific scientific topic. Currently there is one specialty instrument being developed, HIPO – a fast 0.3-1.1 µm CCD system for occultation observations.

Fig. 3 shows the nine 'first-light' SOFIA instruments plotted on the axes of spectral resolution ($\lambda/\Delta\lambda$) and observing wavelength. Looking along the x-axis, it is apparent that the observatory will offer continuous wavelength coverage from the optical to the submillimeter; from 0.35 - 655 µm. The instruments shown in the lower part of the plot operating at low spectral resolution, $R < 10^3$, are infrared cameras that take advantage of SOFIA's large mirror (providing high spatial resolution), little atmospheric obscuration, and a wide field of view.

Looking at the upper right portion of the plot, we see that the observatory features high resolution far infrared and submillimeter spectrometers. These instruments employ gratings (some cross-dispersion), and heterodynes, and will produce background-limited and diffraction-limited spectral line maps that will reveal the astrochemistry of atoms and molecules. Cross-hatched areas on the graph represent goals for additional capabilities that are beyond the basic requirements of the instruments.

CASIMIR (**C**altech **A**irborne **S**ubmillimeter **I**nterstellar **M**edium **I**nvestigations **R**eceiver) will be a submillimeter and far-infrared spectrometer, now under development for the SOFIA airborne

Table 1. First Generation SOFIA Science Instruments

Instrument	Principal investigator	Institute	Type of instrument	Category
CASIMIR	J. Zmuidzinas	Caltech	Heterodyne Spectrometer 250-600 µm, $\lambda/\Delta\lambda = 10^3 ... > 10^7$	PI instrument
EXES	J. Lacy	University of Texas	Echelon Spectrometer 5-28 µm, $\lambda/\Delta\lambda$ = 3000 - 10^5	PI instrument
FIFI LS	A. Poglitsch	MPE Garching	Imaging grating spectrometer 42-210 µm, $\lambda/\Delta\lambda$ = 1400-6500	PI instrument
FLITECAM	I. McLean	UCLA	Near-infrared camera 1-5.5 µm, $\lambda/\Delta\lambda$ = 5-8 (filters) 1000-2000 (grisms) occultation mode	Facility & Test instrument
FORCAST	T. Herter	Cornell University	Mid-infrared camera 5-40 µm, $\lambda/\Delta\lambda$ = 7-20 (filters)	Facility instrument
GREAT	R. Güsten	MPIfR Bonn	Heterodyne spectrometer 63-188 µm, $\lambda/\Delta\lambda = 10^4 ... > 10^7$	PI instrument
HAWC	D.A. Harper	University of Chicago	Far-infrared bolometer camera 40-300 µm, $\lambda/\Delta\lambda$ = 10-20	Facility instrument
HIPO	E. Dunham	Lowell Observatory	High speed imaging photometer 0.3-0.6 µm, 0.4-1.1 µm, $\lambda/\Delta\lambda \leq 100$	Specialty & Test instrument
SAFIRE	H. Moseley	NASA-GSFC	Imaging Fabry-Perot spectrometer 100-655 µm, $\lambda/\Delta\lambda$ = 2000-10^4	PI instrument

observatory as PI-class instrument. As CASIMIR is a heterodyne instrument, it will have extremely high spectral resolution and will be capable of velocity-resolved observations of galactic objects. This instrument will also have very high sensitivity, as a result of the recent advances in superconducting mixer technology, (SIS and HEBs). CASIMIR is very well suited for studying the warm (~100 K) molecular interstellar medium in our own galaxy, as well as in external galaxies. This warm gas is heated by shock waves or UV radiation, processes which are often associated with active star formation. In addition, CASIMIR will be able to study the fundamental rotational transitions of many important hydride molecules. In particular, CASIMIR will be able to study in detail the abundance and excitations of interstellar water, using a number of $H_2{}^{18}O$ transitions.

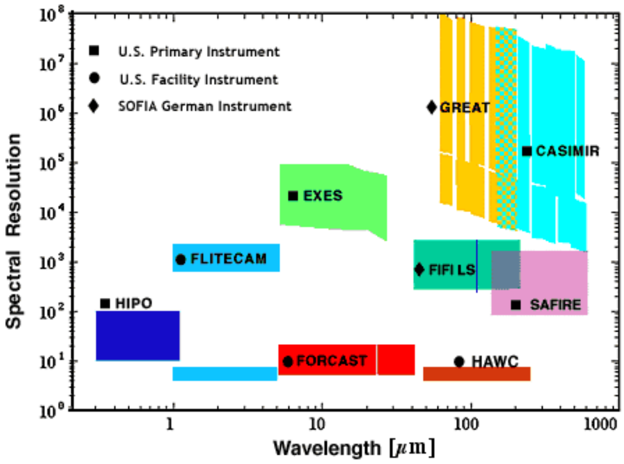

Figure 3. Spectral resolution and wavelength of SOFIA instruments.

EXES (**E**chelon-**C**ross-**E**chelle **S**pectrograph) is build for high-resolution spectroscopy in the mid-infrared. It will operate in three spectroscopic modes: high-resolution ($R = \lambda/\Delta\lambda \sim 10^5$) cross-dispersed; medium-resolution ($R \sim 10^4$) long-slit; and low-resolution (R~3000) long-slit. There will also be an imaging mode suitable for target acquisition. The high spectral resolution enables the study of molecular hydrogen, water vapor, and methane from sources such as molecular clouds, protoplanetary disks, interstellar shocks, circumstellar shells, planetary atmospheres, and comets. For narrow lines associated with point sources, EXES on SOFIA will achieve comparable sensitivity to infrared satellite missions such as ISO and Spitzer.

FIFI LS (**F**ar-**I**nfrared **F**ield-**I**maging **L**ine **S**pectrometer) will utilize the unprecedented high angular resolution and sensitivity of SOFIA to address many key questions in modern astronomy. As a state-of-the-art astronomical instrument, FIFI LS will enable simultaneous observations in two separate bands (42-110 and 110-210 μm) and simultaneous 3D imaging – 2D spatially and 1D spectrally. FIFI LS will provide a unique tool for astronomical 3D spectral imaging of line emission in the far-infrared. Observing in the far-infrared, which is largely unaffected by dust extinction and contains a large number of important emission lines, will allow FIFI LS to make significant contributions to a number of astrophysical problems. The scientific goals and topics include:

- Triggered star formation and the interstellar medium in merging/interacting galaxies.
- The relationship between active galactic nuclei and starburst galaxies.
- The morphology of heating and cooling in galaxies.
- Local and extragalactic star formation.
- The powering mechanism of ultra-luminous infrared galaxies (ULIRGs).
- The interstellar medium in low-metallicity environments (such as dwarf galaxies).

FLITECAM (**F**irst **L**ight **I**nfrared **T**est **E**xperiment **CAM**era) is a facility class multi-purpose near-infrared camera. It is designed to provide a tool for testing the image quality of the SOFIA telescope, including detection of small (~3 mm) black spots on the primary mirror by an optional pupil-viewing mode. In its spectroscopic mode it can also be used to study aircraft exhaust plumes, and provide a calibration of the SOFIA water vapor monitor. A special feature of FLITECAM is that it can be co-mounted for simultaneous operation with HIPO, which will enable both infrared and optical photometry of occultation events. In addition to its role as a test camera, FLITECAM will also produce images for public outreach and for science. FLITECAM is capable of a wide range of scientific projects. In imaging mode, its large field of view will enable surveys of stellar populations in star-forming regions within the Galaxy and nearby galaxies. In spectroscopic mode, the instrument will be able to, for example, distinguish solid CO ice features from gas-phase, and study atomic and rotational-vibrational molecular lines that are obscured from the ground, including Pa α (1.88 μm), Br β (2.63 μm), C_2 (1.4 and 1.8 μm), and C_2H_2 (2.0 and 2.6 μm).

FORCAST (**F**aint **O**bject infra**R**ed **CA**mera for the **S**OFIA **T**elescope) is a facility-class, mid-infrared camera. It has two-channels with selectable filters for narrowband and broadband imaging in the 5-8, 17-25, and/or 25-40 μm regions. Simultaneous imaging in the two-channels ($\lambda < 25$ μm and $\lambda > 25$ μm) is possible. Using 256 x 256 Si:As and Si:Sb blocked-impurity-band detector array technology, FORCAST will sample images at 0.75 arcsec/pixel and will have a 3.2 x 3.2 arcminute instantaneous field-of-view. Imaging is diffraction-limited for $\lambda > 15$ μm. Since FORCAST operates in the wavelength range where seeing from SOFIA is best, it will provide the highest spatial resolution possible from SOFIA. The science projects planned by the investigator team include multicolor imaging of the galactic center, Vega-like circumstellar dust envelopes, and star formation regions in normal and active galaxies. This instrument will be of great value to the astronomical/astrophysical community for imaging of protostellar environments, young star clusters, molecular clouds, and galaxies. Multicolor information will allow determination of dust temperatures, dust optical depths (and dust masses), dust composition, location of ionizing sources, and the spatial morphology of star forming regions.

High-spectral resolution ($\nu/\Delta\nu \geq 10^6$) is required to address a wide range of topics of modern astrophysics, from questions about planetary atmospheres and the interstellar medium in the Galaxy to investigations about the early Universe. With the impressive progress in detector technology over the recent years, the development of sensitive heterodyne receivers for the Terahertz spectral range has now become possible. A consortium of German research institutes has been established for the development of GREAT (**G**erman **RE**ceiver for **A**stronomy at **T**Hz Frequencies), a first-generation dual-channel heterodyne instrument for high resolution spectroscopy aboard SOFIA (German PI-class instrument). A number of unique lines, from atomic fine-structure transitions to fundamental rotational transitions of hydride molecules, will be studied with GREAT. Two examples:

- [CII] 158 µm and [OI] 63 µm fine-structure transitions. The ionized Carbon line is the most important cooling line of the cold interstellar medium, therefore crucial for its energy balance. KAO observations have demonstrated, that on larger scale, the integrated [CII] line intensity is an excellent tracer of the overall star formation activity of a galaxy.
- Observations of the 12 µm ground-state transition of deuterated molecular hydrogen HD will allow the determination of the abundance profile of deuterium across the Galaxy and nearby galaxies, thereby providing critical information on their star formation history and on Big Bang nucleosynthesis models.

HAWC (**H**igh-resolution **A**irborne **W**ide-band **C**amera) is a first-generation facility instrument for SOFIA. It is a far-infrared camera designed to cover the 40-300 micron spectral region at the highest possible angular resolution. HAWC's goal is to provide a sensitive, versatile, and reliable far-infrared imaging capability for the astronomical community during SOFIA's first years of operation. Imagery in this spectral range with the highest possible angular resolution is the natural starting point from which to develop an understanding of source energetics and morphology. It also plays a central role in studies of the physics and chemistry of the interstellar clouds which feed and catalyze the evolution of stars and galaxies. SOFIA's angular resolution will make it possible to study the evolution of stars, planetary systems, and galaxies in unprecedented detail. SOFIA will provide the first far-infrared images which can be directly compared with the wealth of arcsecond-scale data now available at other wavelengths. Its light gathering power will allow studies of many sources in a wide range of environments, from low-mass stars in nearby dark clouds to young star clusters in low-metallicity dwarf galaxies to luminous starbursts in merging galaxies and active galactic nuclei. Some of the scientific problems which will be addressed include the following:

- The formation of stars and stellar clusters within our galaxy.
- Star formation in external galaxies.
- The nature and evolution of protoplanetary and remnant disks around nearby stars.
- The structure and energetics of interstellar clouds.
- The return of gas and dust to the interstellar medium from evolved.
- Conditions in regions surrounding active galactic nuclei.

HIPO (**H**igh-speed **I**maging **P**hotometer for **O**ccultations) is a special-purpose science instrument for SOFIA designed to provide simultaneous high-speed time resolved imaging photometry at two optical wavelengths. It will be possible to mount HIPO and FLITECAM on the SOFIA telescope simultaneously to allow observations at two optical wavelengths and one near-IR wavelength. HIPO will have a flexible optical system and numerous readout modes, allowing many specialized observations to be made. HIPO is also well suited for critical tests of the completed SOFIA Observatory, and will be used for them. The main scientific interest is in the use of HIPO for observing stellar occultations. In a stellar occultation, a star serves as a small probe of the atmospheric structure of a solar system object of the surface density structure of a planetary ring or comet. Such observations provide information at high spatial resolution that would otherwise require a space mission to obtain. This work makes use of SOFIA's mobility, freedom from clouds, and near absence of scintillation noise to provide the best possible occultation data. HIPO will also be well-suited for detection of P-mode stellar oscillations in sunlike stars and for acquiring high S/N multiwavelength light-curves of transits by extrasolar planets.

SAFIRE (**S**ubmillimeter **A**nd **F**ar-**I**nfra**R**ed **E**xperiment) is a versatile imaging Fabry-Perot spectrograph. It will make high sensitivity maps of molecular, atomic, and ionized line emission from objects. These observations are critical to achieving a clear understanding of the processes which result in the formation of stars and which control star formation on a galactic scale in starburst galaxies. SAFIRE will determine the energy balance and physical conditions in many important phases of the interstellar and circumstellar environment in our own galaxy, and will measure the large scale physical conditions in other galaxies. SAFIRE will examine active galactic nuclei, cooling flows in galaxy clusters, and star formation in the most distant galaxies in the Universe. SAFIRE will study objects through the use of many diagnostic lines:

- [CII] 158 µm lines – one of the brightest lines – trace PDRs, atomic clouds, warm neutral medium.
- [OI] 145 µm – probes physical conditions in WNM.
- [NII] 122 µm and 205 µm lines – trace the WIM.
- High-*J* CO lines – trace shocked gas around PDRs.
- OH lines – trace shocks in cool, dense regions.
- [CI] 370 & 609 µm lines – dense gas in clouds.
- Molecular lines – constrain cloud chemistry.

4. PROGRAM STATUS AND OUTLOOK

After successfully passing the functional tests of the telescope for celestial observations from the ground at the end of last year, the development activities are actually focused on the first test flights which will be performed early this year. Once the initial series of closed-door flight tests is completed until mid 2005, further test flights with the door open are planned. The testing of the telescope and the first instruments are scheduled for the end of 2005.

SOFIA is expected to operate for at least 20 years, primarily from NASA Ames Research Center in Moffett Field in California but occasionally from other bases e.g. in New Zealand, Hawaii and Germany. SOFIA will see first light in 2005 with the commencement of observatory performance testing and will be fully operational by 2006.

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