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Stratospheric Observatory For Infrared Astronomy (SOFIA)

E. E. Becklin, L. J. Moon

*University of California Los Angeles, 405 Hilgard Ave, Los Angeles, CA
90095 USA*

*Universities Space Research Association, NASA Ames Research Center,
MS 144-2, Moffett Field, CA 94035, USA*

Abstract. 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 well into development. First science flights will begin in 2004 with 20% of the observing time assigned to German investigators. The observatory is expected to operate for over 20 years. The sensitivity, characteristics and science instrument complement are discussed. SOFIA will have a number of experiments related to Dust Debris Disks; some of these are discussed.

1. Introduction

The Stratospheric Observatory For Infrared Astronomy (SOFIA) is NASA's and DLR's 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 collects radiation in the wavelength range from 0.3 micrometers to 1.6 millimeters.

The telescope and 20% of operations will be supplied by Germany through contracts with DLR (German Space Agency). A team led by the Universities Space Research Association (USRA) has been selected by NASA to design and develop the airborne platform; and to assemble, test, and operate the SOFIA observatory.

The development of the science instruments to be attached to 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 peer review process.

2. SOFIA First Light Instruments

A total of nine instruments have been selected and are now under development (see Table 1). The selection includes three Facility Class (FI) Science Instruments (HAWC, FORCAST, and FLITECAM), five Principal Investigator Class (PI) Science Instruments, and one Special Purpose Principal Investigator Class (SI) Science Instrument (HIPO). Two of the PI Class instruments are being developed in Germany.

Table 1. SOFIA First Light Instruments

Name	PI	Institute	Type of Instrument
HAWC	D.A. Harper	Univ. Chicago	Far IR Bolometer Camera; 30-300 μm
FORCAST	T. Herter	Cornell Univ	Mid IR Camera; 5-40 μm
FLITECAM	I. McLean	UCLA	Near IR Test Camera; 1-5 μm
EXES	J. Lacy	Univ. Texas	Echelon Spectrometer; 5-28 μm , R=1500 & 100,000
CASIMIR	J. Zmuidzinas	Caltech	Heterodyne Spectrometer; 250-600 μm
SAFIRE	H. Moseley	NASA-GSFC	Fabry-Perot Spectrograph; 145-655 μm , R=5-2000
FIFI LS	A. Poglitsch	MPE, Garching	Field Imaging Far IR Line Spectrometer; 40-350 μm
GREAT	R. Guesten	MPIfR Bonn	Heterodyne Spectrometer; 75-250 μm
HIPO	E. Dunham	Lowell Obs.	Visible Occultation CCD; Photometer/Imager

3. First Light Expected in 2004

SOFIA will see first light in 2004, and is planned to make more than 140 scientific flights per year of at least 8 hours 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 μm . 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 housing SOFIA. The SOFIA Program will support approximately 50 investigation teams per year. SOFIA is primarily for use by the U.S. and German science communities, but it is also open to the international science community. Seventy-six percent of the observations will be allocated by a USA peer-review process (managed by USRA), 19% will be allocated by a German peer-review process, and 5% will be allocated at the discretion of the USRA Observatory Director. The USRA Investigator Program is currently being formulated. There will be a mixture of Key Projects, Surveys, Service Observations, and Small Investigations. The latter would be awarded annually; the first two investigation modes could be multi-year projects. The program will also support the development of U.S. science instruments for SOFIA. Some of these instruments will be facility instruments, which will be supported by the SSMOC for use by general investigators. General investigators may also use PI science instruments, but support will be limited. A data cycle system, DCS, for use with facility instruments will allow non-airborne astronomers the ability to easily obtain SOFIA observations in a routine manner. It will also provide an archive of airborne data.

Work on SOFIA is presently being carried out in Germany and the U.S. The Zerodur primary mirror (Figure 1a) has been lightweighted by 80% and polished to its final figure. The secondary mirror (Figure 1b) is made of SiC. Figures 2a and 2b show the bearing sphere and the outer support cradle of the bearing sphere and Nasmyth tube. The aircraft (Figure 3a) has undergone pre-modification test flights to verify and document its performance. The flight tests indicate that SOFIA's performance is significantly better than its predecessor's, the Kuiper Airborne Observatory (KAO). The aircraft is presently being modified to include the open-air cavity door.

Detailed tests and analyses have resulted in several design changes. The telescope will now be built with a hydrostatic bearing rather than an air bearing.

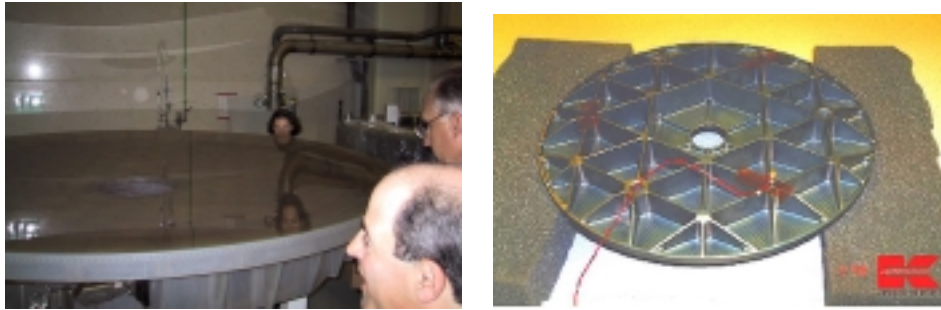


Figure 1. a(*left*) The SOFIA primary mirror is now lightweighted by 80% and polished. b(*right*) The SOFIA SiC secondary mirror blank.

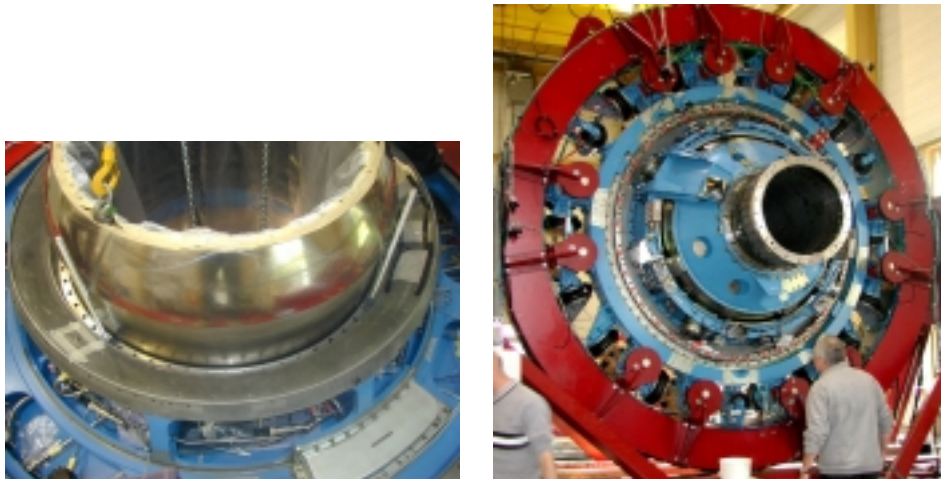


Figure 2. a(*left*) SOFIA hydrostatic bearing. b(*right*) The complete bearing support under test at MAN in Germany.

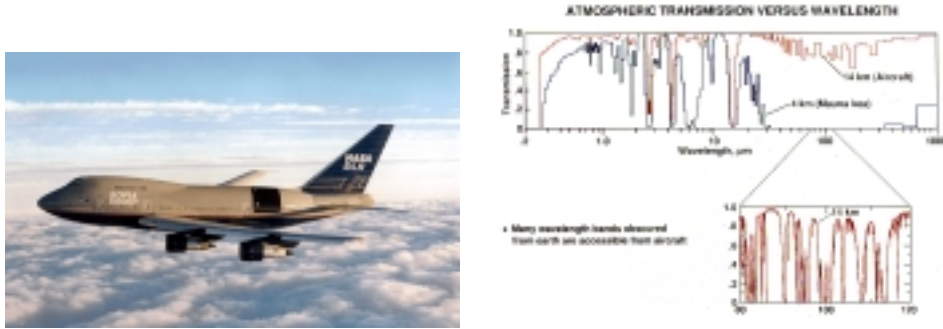


Figure 3. a(*left*) The SOFIA 747-SP aircraft, originally dedicated as the 'Clipper Lindbergh'. b(*right*) Atmospheric transmission as a function of wavelength for aircraft (14 km) and mountaintop (4 km) altitudes. The absorption is largely due to water vapor; figure is from Erickson (1995).

Changes in the aircraft door design have also led to improved telescope and aircraft performance.

4. Science Potential

With the parameters given under SOFIA Characteristics in Table 2, and the atmospheric transmission at flight altitudes given in Traub & Stier (1976) (see Figure 3b) we calculate that the background limited NEFD at 100 μm in a 30% band should be about 400 $\text{mJyHz}^{-1/2}$ and at 450 μm about 300 $\text{mJyHz}^{-1/2}$. The corresponding 1- σ noise in an hour integration should be 7 mJy at 100 μm and 5 mJy at 450 μm . The 1- σ line flux limit in 1 hour should be about $4 \times 10^{-18} \text{ Wm}^{-2}$ at a resolution of 10^3 at 100 μm .

SOFIA will provide a sensitive platform with high spatial resolution for both imaging and spectroscopy at most infrared wavelengths, including those longer than the 200 μm limit of the Infrared Space Observatory (ISO) and Space Infrared Telescope Facility (SIRTF). Figure 4a and Figure 4b show a comparison to other missions.

5. SOFIA Observation of Debris Disks

Observations by IRAS of young nearby stars such as β Pic and Vega have shown the presence of orbiting debris disks. Follow-up observations by ISO, JCMT and HST indicate that these disks might have the presence of H_2 gas (Thi et al. 2001) and have interesting structure that might be an indication of planets (e.g. Holland et al. 1998; Greaves et al. 1998; Schneider et al. 1999).

SOFIA will have the instrumentation and sensitivity to both image and carry out spectroscopy of debris disks around nearby stars. Observation of the H_2 line at 17.0 and 28.2 μm using EXES on SOFIA will allow observations with a signal to noise ratio similar to ISO, but with a much smaller beam (Lacy private communication). Additional debris disks can also be observed for H_2 gas.

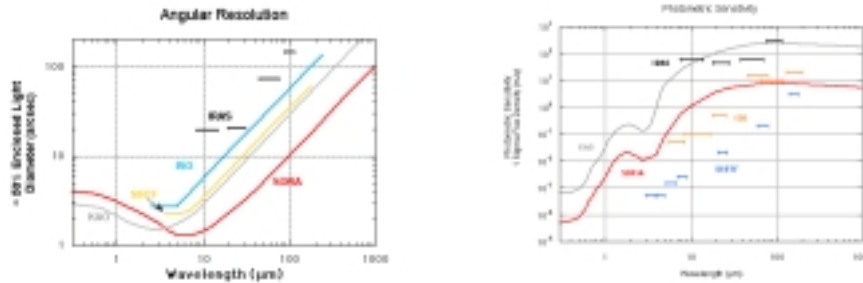


Figure 4. a(left) SOFIA spatial resolution compared with KAO, IRAS, ISO, and SIRTF. b(right) SOFIA photometric point source sensitivities are shown compared with KAO, IRAS, ISO, and SIRTF. On source integration time is 1 hour.

Table 2. SOFIA Characteristics

Nominal Operational Wavelength Range	0.3 to 1600 μm
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 arcmin, 13 arcmin at optimum focus
Maximum Chop Throw on Sky	± 4 arcmin (unvignetted)
Diffraction-Limited Wavelengths	$> 15 \mu\text{m}$
Recovery Air and Optics Temp in Cavity	240K
Image Quality of Telescope Optics (at 0.6 μm)	1.5'' on-axis (80% encircled energy)
Optical Configuration	Bent Cassegrain, chopping secondary and flat folding tertiary
Chopper Frequencies	1 to 20 Hz for 2-point square wave chop
Pointing Stability	$< 1.''0$ 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 μm with dichroic tertiary 10% at 10 μm with aluminized tertiary
Chopped Image Quality due to coma for $\pm 4'$ Chop Throw	$= 9.''1$ for 80% encircled energy diameter $= 5.''8$ for 50% encircled energy diameter

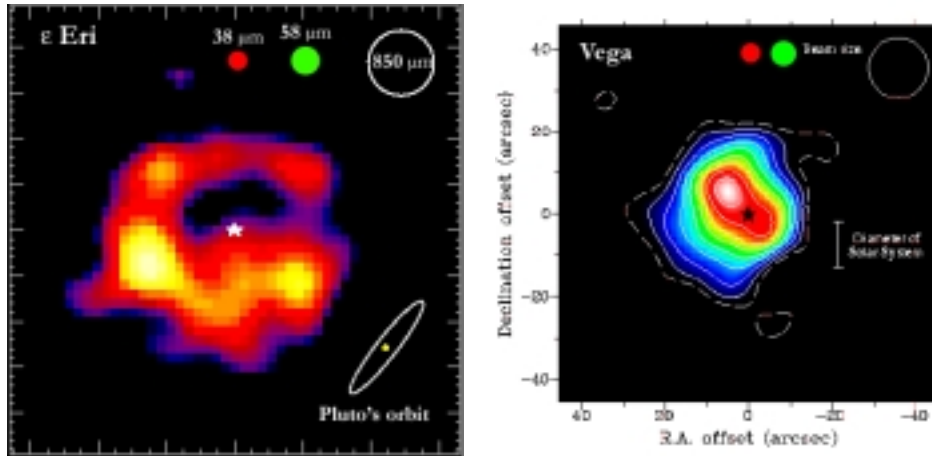


Figure 5. Maps of the (*left*) ϵ Eri and (*right*) Vega debris disk made with the JCMT at $850\ \mu\text{m}$. The smaller SOFIA beam at $38\ \mu\text{m}$ and $58\ \mu\text{m}$ is also shown.

Both FORCAST and HAWC can image the well known debris disks (Vega, Fomalhaut, β Pic, and ϵ Eri) with higher spatial resolution and fidelity than what has previously been possible in the mid and far infrared. With FORCAST a 1 hr integration will yield a $S/N > 5$ per pixel at $38\ \mu\text{m}$ for all of them except the cold ϵ Eri disk.

SCUBA images of debris disks at $850\ \mu\text{m}$ show clear asymmetries in the dust distribution for both ϵ Eri (Greaves et al. 1998) and Vega (Holland et al. 1998), which could be caused by Jupiter sized planets. Wilner et al. (2002) mapped Vega with Plateau deBure Interferometer at $1.3\ \text{mm}$ and resolved the dust emission into two blobs, but with low S/N . SOFIA can do much better, and these stars will be prime targets for first light observations.

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