Part 9

Future Prospects

Brown Dwarfs
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Stratospheric Observatory For Infrared Astronomy (SOFIA)

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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. 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 Brown Dwarf research; 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.

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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. 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 (Fig. 1a) has been lightweighted by 80% and polished to its final figure. The secondary mirror is made of SiC (Fig. 1b). Figure 2a shows the 1.2 meter hydrostatic bearing being assembled and figure 2b shows the outer support cradle of the bearing sphere and Nasmyth tube. The aircraft (Fig. 3a) has undergone pre-modification test flights to verify and document its performance; the aircraft is presently being modified to include the open-air cavity door.

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 mJyHz$^{-1/2}$ and at 450 μm about 300 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 $\times$

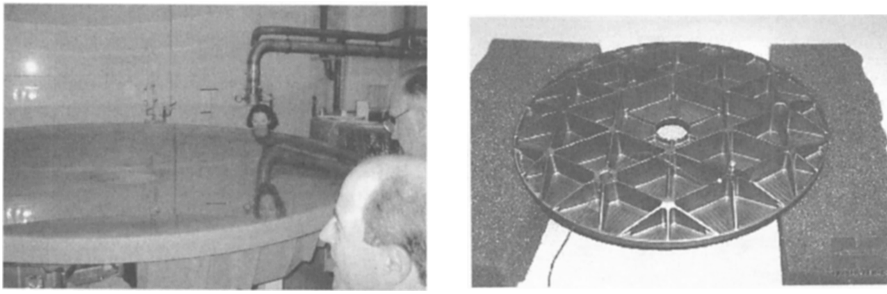

Figure 1. a(*left*) The SOFIA primary mirror is now lightweighted by 80% and polished. b(*right*) The SOFIA SiC secondary mirror blank.

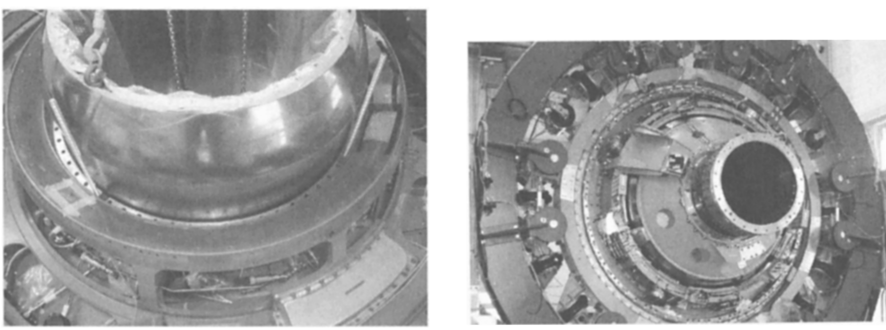

Figure 2. a(*left*) SOFIA hydrostatic bearing. b(*right*) The complete bearing support under test at MAN in Germany.

10^{-18} Wm^{-2} at a resolution of 10^3 at 100 μm. Figures 4 and 5 show the SOFIA performance relative to other missions.

5. Brown Dwarf Science with SOFIA

Spatially Resolved Spectra of Jupiter

The understanding of the atmospheric structure of brown dwarfs has been helped by the extensive knowledge of Jupiter. SOFIA allows studies of Jupiter's atmosphere that have not been done, especially with regards to high resolution spectroscopy combined with high spatial resolution. Unique studies of the cloud and composition can be done with EXES, GREAT and CASIMIR on Jupiter.

Stellar Occulation of Extra Solar High Mass Planets & Brown Dwarfs

The discovery of stellar occulations of a high mass planet has opened up a new frontier of research (Charbonneau et al. 2000 & Henry et al. 2000). More occultation candidates will be found in the radial velocity studies (i.e. Mayor & Queloz 1995) and by larger field searches such as Kepler (Koch et al. 1998). SOFIA can advance these studies in two ways

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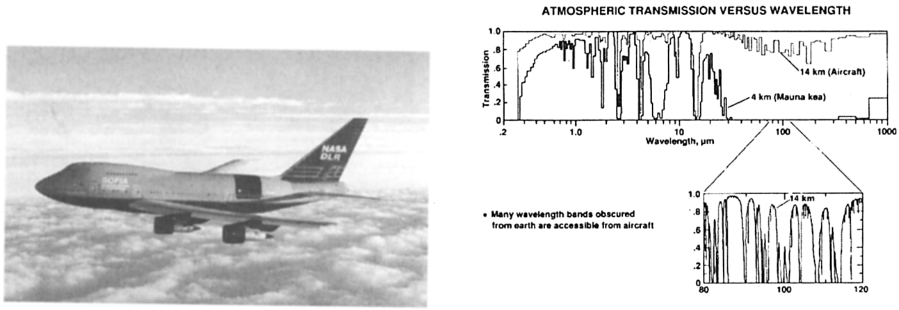

Figure 3. a(*left*) The SOFIA 747-SP aircraft, originally dedicated the 'Clipper Lindbergh'. b(*right*) Atmospheric transmission as a function of wavelength for aircraft (14 km) and mountaintop (4 km) altitudes. Absorption is largely due to water vapor; figure from Erickson (1995).

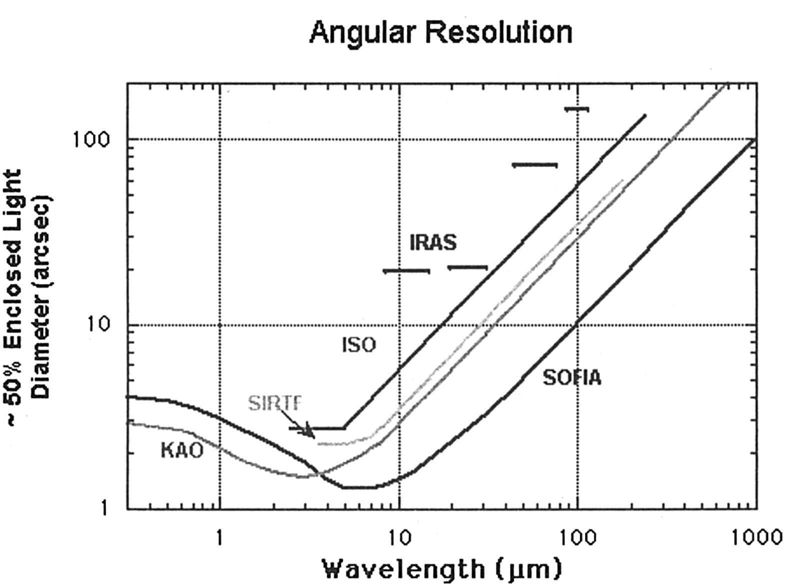

Figure 4. SOFIA spatial resolution compared with KAO, IRAS, ISO, and SIRTF.

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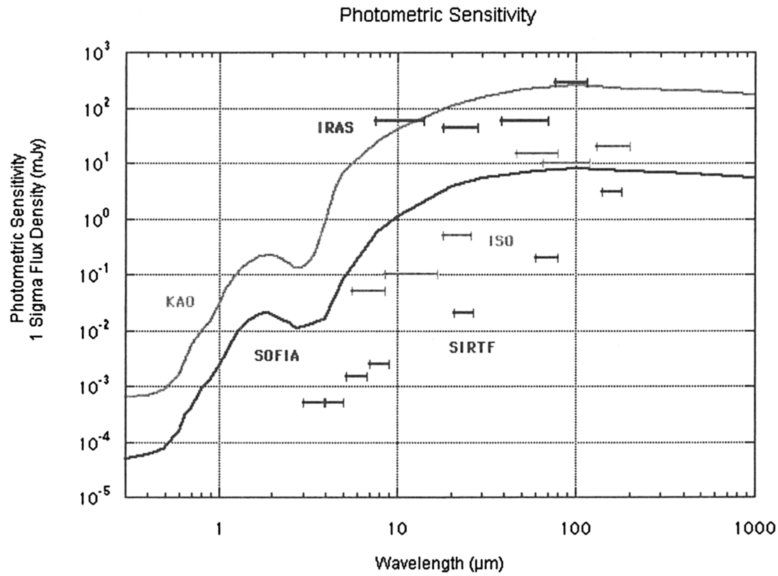

Figure 5. SOFIA photometric point source sensitivities are shown compared with KAO, IRAS, ISO, and SIRTF. On source integration time is 1 hour.

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	$\pm$ 4 arcmin (unvignetted)
Diffraction-Limited Wavelengths	$>$ 15 μm
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

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1) Scintillation noise will be very low with HIPO. Extrapolating a commonly used ground based model (Dravins et al. 1998) to stratospheric altitudes indicates a noise floor of $4x10^{-5}$ in 15 minute integration. The fact that SOFIA operates above the tropopause suggests that this model will break down, further suggesting that there will be in fact less scintillation noise (Sandell et al. 2003)

2) Use of FLITECAM with HIPO, allows observations of the entire wavelength range from 0.3 to 5 μm. This includes potential strong atmospheric bands due to CH_4 and water.

Energy Distributions of Brown Dwarf Clumps in Nearby Star Formation Regions

Submillimeter maps of star formation regions show individual clumps of dust with a total mass in gas and dust in the brown dwarf range. (i.e. Sandell & Knee 2001). It is assumed that these clumps will form brown dwarfs. To understand these clumps, we nee d to determine their dust temperature and luminosity. This requires SOFIA measurements at 30 to 200 μm with the highest angular resolution possible to avoid confusion (See figure 4).

Spectral Energy Distribution of the Nearest Brown Dwarfs

If ρ(B.D.) $\sim$ ρ(stars) as has been noted in this conference and other places (Gizis et al. 2000), then the nearest brown dwarf will be ~1 pc away. If its mass is 25 M_{jup} and its age $5x10^9$ yrs, then from models its luminosity w ill be $\sim 6x10^{-7}$ L$\odot$ and $T_e \sim$ 500K. Extrapolating from known brown dwarfs and models, we would expect a 5 and 10 μm flux density of 10 and 25 mJy respectively. This would easily be discovered in a future all sky mid-infrared survey such as NGSS discussed by Kirkpatrick at this conference. SOFIA will be able to obtain a R~50 measurement of the energy distribution from 5 to 28 μm, as well as a 40 μm photometric point.

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References

Charbonneau, P. et al. 2000, ApJ, 529, L41

Dravins, D. et al. 1998, PASP, 110, 610

Erickson, E.F. 1995, Space Science Reviews, 74, 91

Gizis, J. et al. 2000, A.J. 120, 1085

Henry, G.W. et al. 2000, ApJ, 529, L45

Koch, D. et al 1998 in SPIE conf. proc. vol. 3356, Space Telescopes and Instruments V, ed P. Bely & J. Breckinridge, 599

Mayor, M. and Queloz, D 1995, Nature, 378, 355

Sandell, G, Becklin, E.E. & Dunham, T. 2003, in ASP conf. ser., Scientific Frontiers in Research on Extrasolar Planets

Sandell, G & Knee, L.B.G. 2001, ApJ, 546, L49

Traub, W.A. & Stier, M. 1976, Applied Optics, 15, 364