THE SOFIA PROGRAM*

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ABSTRACT

SOFIA, the Stratospheric Observatory for Infrared Astronomy, is a Boeing 747 SP airplane with a 2.5 m effective diameter telescope, a joint project of NASA in the U.S. and the DLR in Germany. It is designed to operate at altitudes from 12 to 14 km and wavelengths from 0.3 µm to 1.6 mm over a 20-year lifetime. The telescope will be diffraction limited at wavelengths beyond roughly 15 µm, for example producing a point-spread function ~8.5 arc seconds FWHM at 100 µm. SOFIA's mobility will allow coverage of the entire sky and enable unique observations of ephemeral events. Nine first-generation focal plane instruments are being built, with more to be added later. These attributes assure SOFIA a vital role in future studies of the interstellar medium and the solar system, as well as other disciplines. Topics discussed here are: scientific rationale, the observatory and its relation to other facilities, the science instruments, some science examples, the program status, and observing plans.

1. SCIENCE RATIONALE

The interstellar medium (ISM) plays a central role in the evolution of our own and other galaxies. The ISM is the repository of stellar ashes, injected by both gentle winds and cataclysmic explosions. The effluent gas and condensing dust eventually become raw materials from which new stars and planetary systems form. Enrichment with synthesized elements accompanies the stellar life cycle, driving galactic evolution. Solid particles and molecular, neutral atomic, and ionized gas in the ISM are characterized by numerous spectral features at infrared and submillimeter wavelengths which enable astrophysics not possible in other bands. Similarly, luminosities of embedded sources are often revealed only as infrared re-radiation by interstellar dust grains; the corresponding spectral energy distributions (SEDs) yield important information about the sources and the obscuring material. Magnetic fields may align interstellar grains resulting in polarized far infrared (FIR) emission, which can be sensed by polarimetric measurements.

With SOFIA [1,2], observers will explore the gamut of ISM topics: star formation; the Galactic Center; debris disks; recycling of materials through the stellar life cycle; the origin and evolution of biogenic materials; shock, photodissociation, and photoexcitation physics; and gas and grain chemistry. Imaging, spectroscopy, and eventually polarimetry covering much of the infrared spectrum will all be part of SOFIA's arsenal in the attack on these and other important problems.

Equally fundamental topics in solar-system science will also be studied from SOFIA. These include composition and structure of planetary and satellite atmospheres and rings, chemistry in comets, and sizes and orbits of Kuiper-belt objects. Extra-solar planet transits should also be observable.

SOFIA's main attributes are shown in Table 1. Basically, SOFIA will be a mobile "ground-based" observatory operating in the lower stratosphere. SOFIA's long life and accessibility will foster new instrument technology applications and permit vigorous education and public outreach activities, as well as enabling a unique science program.

Table 1. Basic SOFIA Attributes

Feature	Characteristic
Wavelength Range	0.3 – 1600 µm, "UV to Radio"
Mobility	All-sky coverage, ephemeral events "anywhere, any time"
Primary Mirror	2.7 m diameter (aperture 2.5 m)
Operating Altitude	12 – 14 km (37,000 – 45,000 feet)
Design Lifetime	20 years
Observing Program	flexible, annual proposal opportunities, international community
Science Instruments	9 first-generation; in-flight access; new instrument technologies
Education/Public Outreach	teachers, media, public participation

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2. COMPARISON WITH OTHER FACILITIES

As with the KAO and shown in Fig. 1, SOFIA will provide wavelength coverage and temporal continuity unmatched by other facilities operating at far-infrared wavelengths.

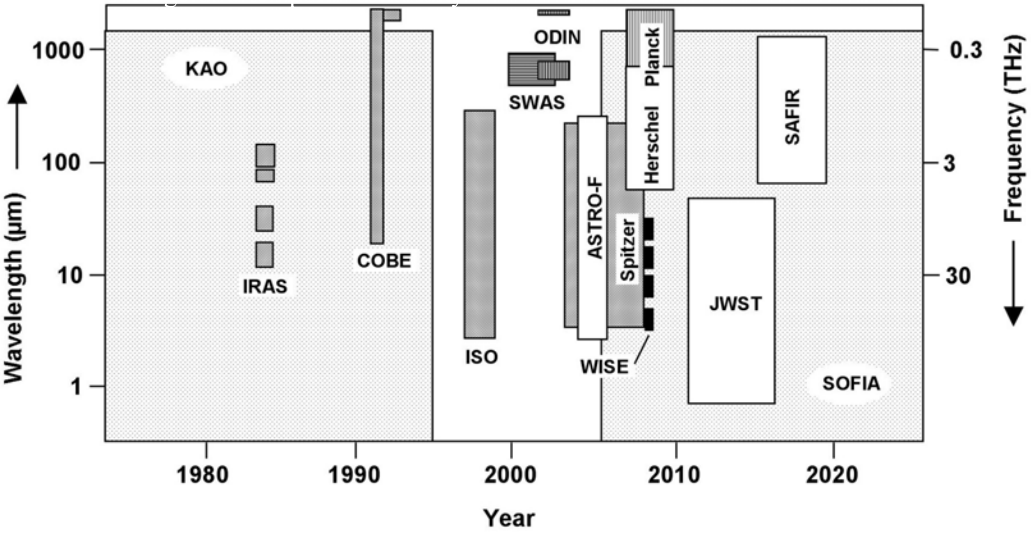

Fig. 1. Far-Infrared Facilities 1975 – 2025: wavelength coverage versus epoch.

The SOFIA and Herschel telescopes are factors of 3 to 4 larger in diameter than those previously operating in the FIR, as shown in Table 2. Their diffraction limited angular resolutions (~λ/D, where D is the effective telescope diameter and λ is the wavelength) will be the highest available in the FIR this decade.

Table 2. Mid- and Far-Infrared Telescope Diameters 1975 - 2025

Telescope	KAO	IRAS	ISO	ASTRO-F	Spitzer	SOFIA	Herschel	WISE	JWST	SAFIR
Diameter (m)	0.91	0.6	0.6	0.7	0.85	2.7	3.5	0.4	6.5	8 - 10

Fig. 2 plots the wavelength coverage of "high" angular resolution infrared facilities as a function of wavelength. Juxtaposed with the same wavelength scale is the atmospheric transmission at low spectral resolution, for aircraft and high ground-bound sites. The latter receive practically no 30-300 µm light.

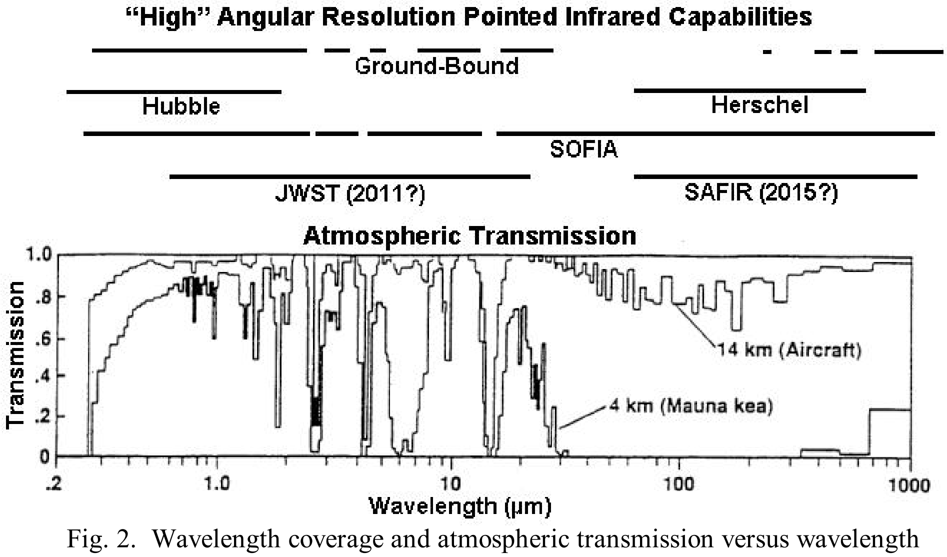

Fig. 2. Wavelength coverage and atmospheric transmission versus wavelength

In Fig. 3 the atmospheric transmission T is plotted at a resolving power R of 10,000, in the range from 145-165 µm. The top curve is for an altitude of 12.5 km and 7 µm of precipitable water vapor (PWV), corresponding to the transmission from SOFIA. Even at aircraft altitudes there are saturated telluric water lines, but most wavelengths have useable transmissions. For example, an important coolant of gas in the ISM is [C II] at 158 µm, for which T ~ 90%. The lower curve is for an altitude of 2.8 km and 250 µm PWV, corresponding to a good night at Dome C in the antarctic, arguably the driest earth-bound site; its transmission can be up to a few percent in the ~149-154 µm range, but is negligible elsewhere in this band.

Figure 4 plots the angular resolution of FIR telescopes which have been or are expected to be operational by the end of the decade. They are diffraction-limited at the longer wavelength end of their useful ranges, as mentioned above. For SOFIA, seeing from the turbulent shear layer over the open port telescope will produce a point-spread function with encircled energy diameter ~2-4 arc seconds (") in the visible. In the near infrared, telescope optical quality and pointing stability will limit image quality to ~1-2". The pointing stability [3] is difficult to achieve and to predict because of the aerodynamic loads on the telescope.

SOFIA's telescope will operate at temperatures ~240 K as did the KAO's. This is much warmer than the other telescopes listed in Table 2. Science instruments viewing a warmer telescope will experience higher photon backgrounds. Direct (incoherent) detector systems with comparable optical bandwidths will therefore experience higher noise on SOFIA than on the colder telescopes. Fig. 5 shows the resulting background-limited sensitivities for direct photometric detection, accounting for temperature, emissivity, and size. For example, Herschel's imagers will be roughly 10 times as sensitive per pixel as SOFIA's at the same wavelengths. Higher resolution spectrometers with direct detectors on SOFIA experience lower backgrounds and are not represented in the Figure. The first generation heterodyne receivers on SOFIA will be comparable in sensitivity to those on Herschel.

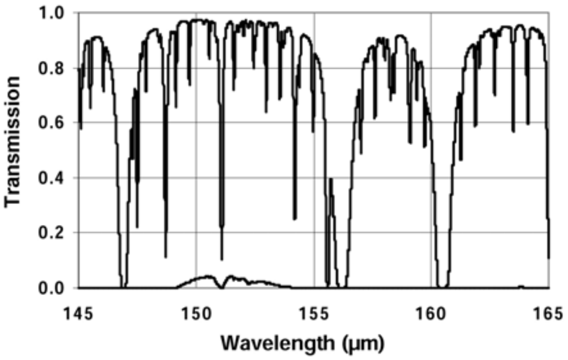

Fig. 3. Atmospheric transmission at R = 10,000.

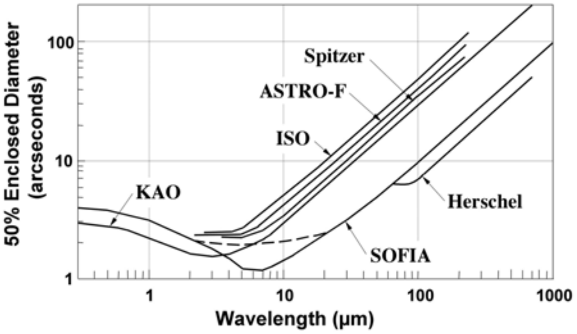

Fig. 4. Angular resolution of FIR telescopes

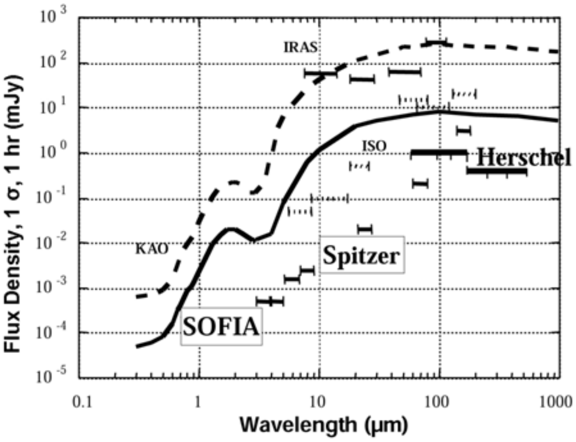

Fig. 5. Photometric sensitivity of FIR facilities.

3. SOFIA SCIENCE INSTRUMENTS

Nine SOFIA science instruments have been under development since 1997. They are in various stages of development by Science Instrument (SI) teams at their home institutions. The instruments are listed in Table 3, in the approximate order in which they will be commissioned for flight. HAWC, FORCAST, and FLITECAM are classified as "Facility Instruments", with the intent that they will be maintained and operated for General Observers (GOs) by the observatory staff. The remainder of the instruments are classified as "PI" instruments. These will be maintained and operated by the developers for collaborative investigations with GOs and for their own investigations. After some initial guaranteed-time observations for the SI teams, all observing time will be competitively awarded, with the exception of director's discretionary time and engineering time.

Table 3. First generation SOFIA science instruments.

Instrument	Type	λλ (μm)	Resolution	PI	Institution
HIPO	fast imager	0.3 - 1.1	filters	E. Dunham	Lowell Obs.
FLITECAM	imager/grism	1.0 - 5.5	filters/R~2E3	I. McLean	UCLA
FORCAST	imager/(grism?)	5.6 - 38	filters/(R~1E3?)	T. Herter	Cornell U.
GREAT	heterodyne receiver	158 - 187, 110 - 125, 62 - 65	R ~ 1E4 - 1E8	R. Güsten	MPIfR
CASIMIR	heterodyne receiver	250 -264, 508 -588	R ~ 1E3 -1E8	J. Zmuidzinas	CalTech
FIFI LS	imaging grating spectrograph	42 - 110, 110 - 210	R ~1E3 - 3E3	A. Poglitsch	MPE
HAWC	imager	40 - 300	filters	D. A. Harper	Yerkes Obs.
EXES	imaging echelle spectrograph	5 - 28.5	R ~ 3E3 - 1E5	J. Lacy	U. Texas Austin
SAFIRE	imaging F-P spectrometer	150 - 650	R ~ 1E3 - 2E3	H. Moseley	NASA GSFC

The HIPO and FLITECAM instruments are operational and have both taken data at two telescopes. These instruments and FORCAST and EXES use commercially available detector arrays. The detectors and receivers for the remainder of the instruments are all developmental devices that the SI teams are continuing to refine, most often in collaboration with scientists at other laboratories sharing similar interests. These "high-tech" detectors are a major part of the overall effort in building the instruments. All the SI teams have prepared "Flyers" describing their instruments. Some upgrades are being considered, e.g., grisms for FORCAST. Performance summaries describing the instruments' sensitivities, angular, and spectral resolutions, and an analysis summarizing atmospheric effects on observations are also available [4,5]. Fig. 6 plots the instruments' spectral resolutions versus wavelength, and cites some of the associated potential science investigations.

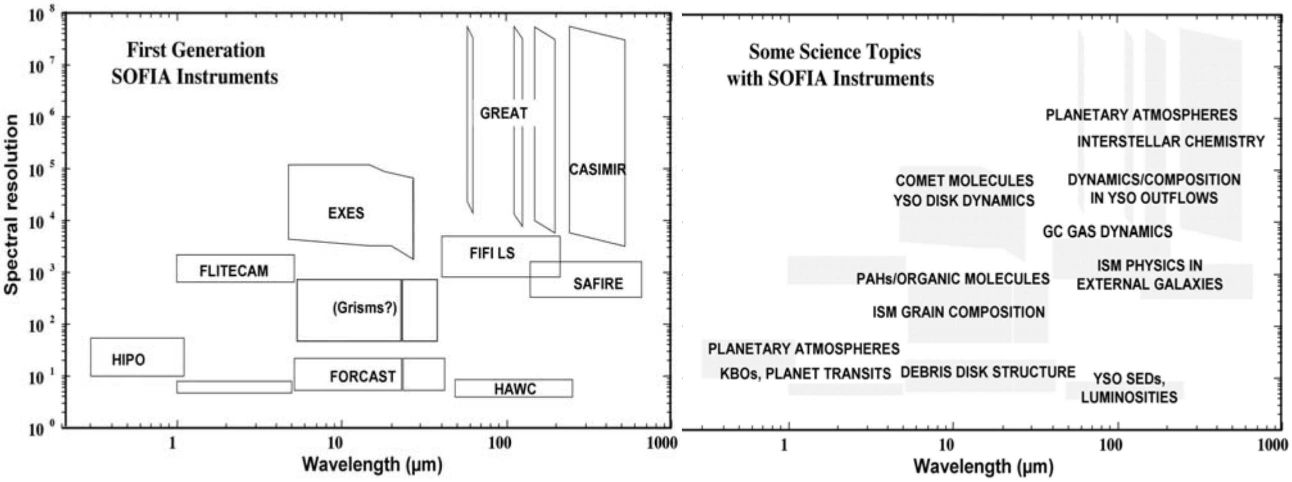

Fig. 6. SOFIA instruments: spectral resolving power versus wavelength, and some relevant science topics.

4. SOME EXAMPLES OF SOFIA SCIENCE

Ephemeral Events:

SOFIA's mobility gives it unique capabilities for observing any part of the sky during astronomical events of short duration. For example, the shadow of a solar system object (SSO) cast by a star may appear anywhere on earth, traveling up to 30 km/s. SOFIA will enable HIPO and FLITECAM to observe - simultaneously - the light from the occulted star to obtain details of planetary atmospheres, ring systems, and other SSOs on scales of a few kilometers. The rings of Uranus were discovered from the KAO by this technique. It should be possible to measure the sizes of some 30 Kuiper Belt Objects as small as 200 km to constrain their albedos. A number of such occultation events should be possible each year. In addition, the absence of scintillation noise will allow observation of extrasolar planet transits with signal-to-noise comparable to that from HST.

HD in the ISM

The D/H abundance ratio traces nuclear evolution and astration in the ISM. In cold, dense prestellar cores and protostellar disks associated with early star formation, the abundance of gas-phase deuterated molecules can be dramatically enhanced. Observations of molecular D/H probe temperatures, ionization fraction, and gas-grain interactions [6]; the latter are critical for understanding the fundamental but obscure process of H_2 formation. HD is at the root of the deuterium chemistry network (Fig. 7). Observations of the 112 µm line of HD will be a priority for the GREAT heterodyne spectrometer. Its high resolution will minimize the problem of line-to-continuum ratio often encountered in observing narrow lines in the ISM. Possibly, the HD line may be used to trace the column density of H_2 in molecular clouds.

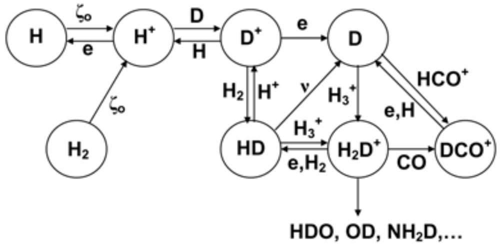

Fig. 7. Deuterium chemistry network.

AGN Structure

Differences in Seyfert galaxy types may simply be due to viewing angle. Unification models of these AGNs feature a torus of hot (~1000 K) molecular gas obscuring the central black hole engine (Fig. 8). The torus is predicted to produce strong high-J CO line emission, peaking at J = 58 – 57 (λ = 46 µm) [7]. FIFI LS will detect a number of these mid- to high-J CO lines in ~1h of integration, to test this picture of AGN structure.

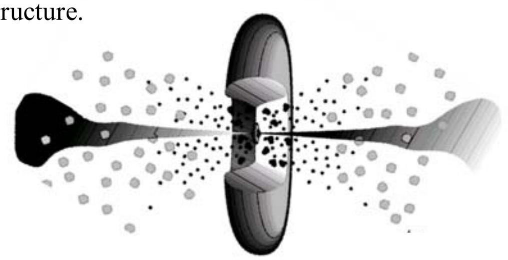

Fig. 8. Cartoon of AGN model.

Disk Structure and Chemistry

The inner structure of circumstellar disks may be revealed by the shape of emitted spectral lines. Fig. 9 shows calculated H_2 line profiles for a protostellar disk with and without a gap at 3 AU. Disk clearing is thought to occur when planets are forming, and this technique may be one of the few ways to probe disk structures on this scale. For example, ALMA will image the millimeter dust continuum and CO emission, resolving scales ~10 AU, to examine morphology and to estimate dust and gas content. From SOFIA, EXES, with ~3 km/s resolution, will target disk systems to constrain gas mass, morphology, and chemistry. Some lines expected are H_2 (28 µm), [S I] (25 µm), and [Fe II] (26 µm) [8]. Also lines of H_2O, CH_4, and CO should be detectable, and possibly HCN and C_2H_2.

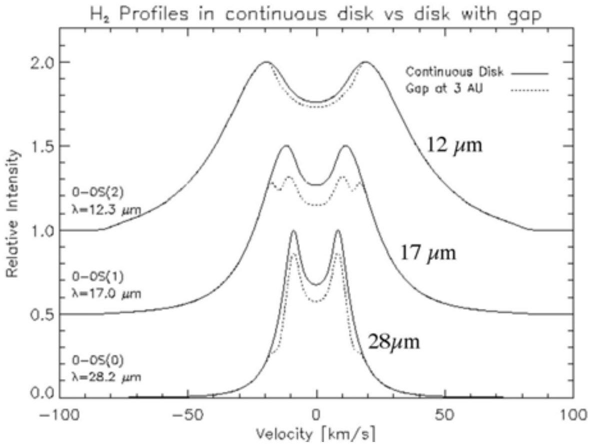

Fig. 9. Theoretical H_2 line profiles from disks.

The Galactic Center

Observations of FIR lines from the KAO found that gas in the peculiar thermal radio filaments appears to be excited by radiation from stars with T_{eff} ~ 35,000 K. This led to the discovery (from the Anglo-Australian telescope) of the nearby "Arches Cluster" of hot stars with a luminosity ~$2x10^7$ L_{sun}. Subsequent KAO photometric imaging at 38 µm [9] suggests that additional sources may be required to power emission from the filaments. FORCAST will image them with < 4" (<0.2 pc) resolution at wavelengths up to 38 µm to seek evidence for possible embedded heating sources.

The massive black hole lurking at Sgr A* is enigmatically faint. Gas motion, distribution and excitation in its vicinity can provide clues to the apparently low accretion rate. Narrow band filter images in the [Si II] 34.8 µm line by FORCAST, and GREAT measurements of the morphology and dynamics of the [O I] 63 µm line, will map the photo-dissociated and neutral gas. FIFI LS will obtain density and excitation estimates from the [O III] 52 and 88 µm lines. Together these data will yield important clues for the faintness of our local massive black hole.

5. PROGRAM STATUS

The modification of SOFIA's Boeing 747 SP aircraft is being done by L-3 Communications Corporation in Waco, Texas. The telescope was developed by MAN and Kaiser Threde in Germany, and has been installed in the aircraft. In May 2004, the aircraft and telescope successfully passed a test demonstrating the integrity of the entire pressure vessel. In August 2004 functional testing of the telescope pointing and control system was done on the ground in Waco, while observing stars in the telescope guide cameras and with HIPO at the focal plane. Currently the fuselage modifications are being completed, the cavity door that covers the open port over the telescope is being installed, and the aircraft is being readied for airworthiness test flights anticipated in 2005.

The Mission and Operations Center is in hangar N-211 at NASA Ames Research Center in California. This building will house all elements of the program: the aircraft, offices for science and flight operations staff and investigators, instrument laboratories, the primary mirror coating chamber, maintenance facilities, and shops, etc. The science operations and information systems groups already occupy their offices there.

6. OPERATIONS PLANS

NASA has contracted with the Universities Space Research Association to manage the U.S. science operations, to be led by Professor Eric Becklin. Evergreen Air was selected as the interim flight operations contractor. The DLR has contracted with the University of Stuttgart to manage the Deutsche SOFIA-Institut, under Professor Hans-Peter Röser.

First science flights are expected in 2006, beginning with commissioning of several of the science instruments, and ramping up to the full flight program with all the instruments over a period of two years. SOFIA is designed to fly ~ 1000 hours per year, but the target number will be adjusted to maximize science productivity by balancing flight time with new instrument development. For example, significant improvements in sensitivity, frequency range and imaging can be expected for heterodyne receivers.

General Observers will be able to propose measurements with any of the science instruments; descriptions and performance summaries are now on the SOFIA website. GO participation in observations will be recommended but not mandatory. Observing proposals will be accepted annually by a U.S. peer review for 80% of the available observing time, and by a German peer review for the remaining 20%. International proposals may be submitted to either review. Competitive opportunities are anticipated for early demonstration science in the limited observing time available during the ramp-up period.

In conclusion, SOFIA construction is nearing completion, with significant testing to follow, preceding full scale science operations. SOFIA will provide unique scientific capabilities complementing other facilities, will encourage and accommodate application of new instrument technologies, and will foster a strong program of education and public outreach. Observing opportunities will be available to the entire international astronomical community. ***Come fly with us!*** http://sofia.arc.nasa.gov

7. ACKNOWLEDGEMENTS

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