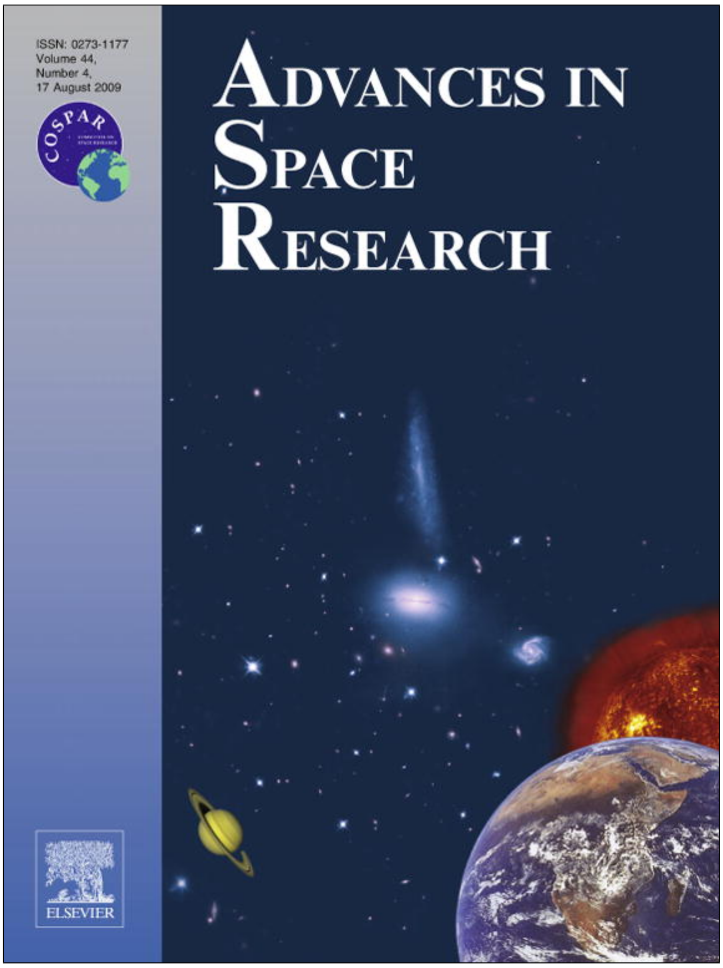
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A new window on the cosmos: The Stratospheric Observatory for Infrared Astronomy (SOFIA)

R.D. Gehrz [a,*], E.E. Becklin [b], I. de Pater [c], D.F. Lester [d], T.L. Roellig [e], C.E. Woodward [a]

[a] Department of Astronomy, School of Physics and Astronomy, 116 Church Street, S.E., University of Minnesota, Minneapolis, MN 55455, USA
[b] Universities Space Research Association, NASA Ames Research Center, MS 211-3, Moffett Field, CA 94035, USA
[c] Astronomy Department, University of California Berkeley, 601 Campbell Hall, Berkeley, CA 94720, USA
[d] Department of Astronomy, University of Texas at Austin, 1 University Station C1400, Austin, TX 78712, USA
[e] NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035, USA

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Abstract

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a joint US/German Project to develop and operate a gyrostabilized 2.5-m telescope in a Boeing 747-SP. This observatory will allow astronomical observations from 0.3 μm to sub-millimeter wavelengths at stratospheric altitudes as high as 45,000 ft where the atmosphere is not only cloud-free, but largely transparent at infrared wavelengths. The dynamics and chemistry of interstellar matter, and the details of embedded star formation will be key science goals. In addition, SOFIA's unique portability will enable large-telescope observations at sites required to observe transient phenomena and location specific events. SOFIA will offer the convenient accessibility of a ground-based telescope for servicing, maintenance, and regular technology upgrades, yet will also have many of the performance advantages of a space-based telescope. Initially, SOFIA will fly with nine first-generation focal plane instruments that include broad-band imagers, moderate resolution spectrographs that will resolve broad features from dust and large molecules, and high resolution spectrometers capable of studying the chemistry and detailed kinematics of molecular and atomic gas. First science flights will begin in 2010, leading to a full operations schedule of about 120 8–10 h flights per year by 2014. The next call for instrument development that can respond to scientifically exciting new technologies will be issued in 2010. We describe the SOFIA facility and outline the opportunities for observations by the general scientific community with cutting edge focal plane technology. We summarize the operational characteristics of the first-generation instruments and give specific examples of the types of fundamental scientific studies these instruments are expected to make.

Keywords: Infrared astronomy; Sub-millimeter astronomy; Airborne astronomy; Infrared spectroscopy; SOFIA; NASA

1. Introduction

The NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA, SOFIA Project Website, 2009) consists of a Boeing 747-SP aircraft housing a 2.5-m telescope (Fig. 1) designed to make sensitive measurements of a wide range of astronomical objects at wavelengths from 0.3 μm to sub-millimeter wavelengths. This new observatory will be a key element in our research portfolio for chemical and dynamical studies of warm material in the universe, as well as for observations of deeply embedded sources and transient events. SOFIA is designed and planned for at least two decades of operations and will join the *Spitzer Space Telescope* (Werner et al., 2004; Gehrz et al., 2007), *Herschel Space Observatory* (Pilbratt, 2003), and *James Webb Space Telescope* (JWST, Gardner et al., 2006) as one of the primary facilities for panchromatic

* Corresponding author. Tel.: +1 612 624 7804; fax: +1 612 626 2029.
E-mail address: gherz@astro.umn.edu (R.D. Gehrz).

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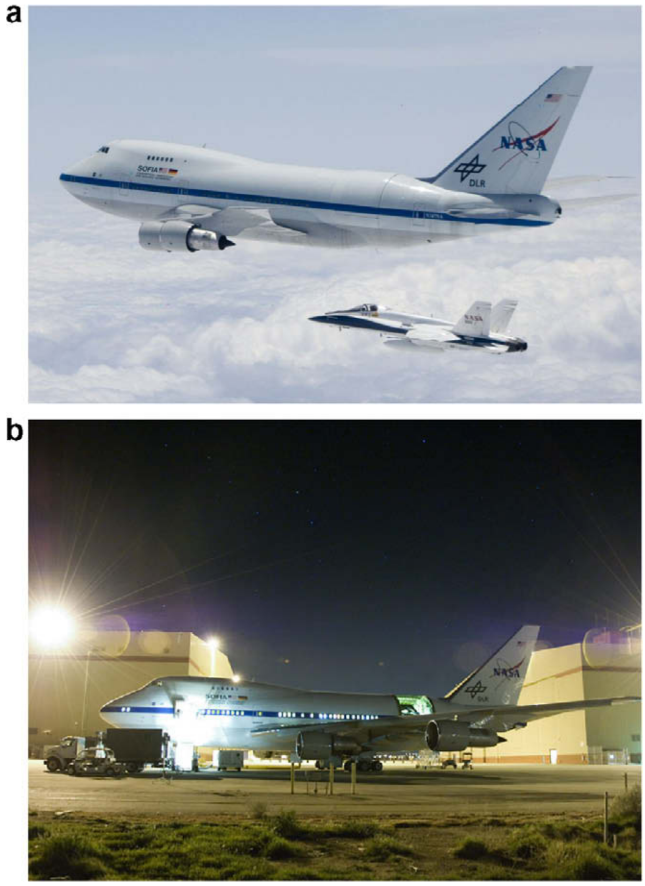


Fig. 1. The NASA/DLR SOFIA infrared observatory: (top) with F/A-18 safety chase during the first series of test flights to verify the performance of the modified Boeing 747-SP, and (bottom) during night-time telescope characterization tests at Palmdale, CA Site-9 in March 2008. NASA Dryden Flight Research Center Photo Collection.

observations in thermal IR and sub-millimeter astronomy. Furthermore, SOFIA will be a test bed for new technologies and a training ground for a new generation of instrumentalists.

SOFIA is funded jointly by NASA and the German Space Agency (DLR), with the two agencies splitting the operational costs and science time usage by 80% and 20%, respectively. The NASA Science Mission Directorate is open to considering proposals for participation as a partner in the United States's share of the operations phase of the SOFIA mission by domestic and international governments, agencies, universities, organizations, and research foundations.

The SOFIA telescope design and its evolving instrument complement build upon the heritage of NASA's Kuiper Airborne Observatory (KAO, Gillespie, 1981), a 0.9-m infrared telescope that flew from 1971 to 1995 in a Lockheed C141 Starlifter aircraft. SOFIA will see first light in 2009, and will be capable of making more than 120 8–10 h scientific flights per year for at least 20 years. The SOFIA Science and Mission Operations Center (SSMOC) is responsible for the science productivity of the mission, and is located at NASA Ames Research Center in Moffett Field, CA. Flight operations will be conducted out of NASA Dryden Flight Research Center's Aircraft Operations Facility in Palmdale, CA. The Universities Space Research Association (USRA) and the Deutsches SOFIA Institut (DSI) in Stuttgart, Germany manage science and mission operations for NASA and DLR.

The SOFIA Program will support approximately 50 science teams per year, selected from peer reviewed proposals. An ongoing instrument development program will ensure that this easily serviceable facility remains state-of-the-art during its lifetime. The next call for new generation instruments will occur in 2010. Science operations will start with a phased approach in order to best utilize the platform to guide scientific optimization of the observatory and the development of its next generation of instruments. Early Science with the FORCAST and GREAT instruments (described in Section 2 below) will occur in 2010, in response to proposals solicited during 2008. The first science flights, limited in scope, will be predicated on science collaboration with the Principal Investigators (PIs) of those instruments in order to ensure Early Science productivity. Routine observations will begin in 2010 in response to General Observer (GO) science proposals solicited in 2009. There will be new science proposal solicitations every 12 months thereafter. About 20 GO science flights are planned annually at the start of science operations, with the annual flight rate ramping up steadily until the full ~100 annual rate is achieved in 2014.

1.1. SOFIA's operational envelope and range

Flying at altitudes up to 45,000 ft (13.72 km) where the typical precipitable atmospheric water (H_2O) column depth is less than 10 μm (a hundred times lower than at good terrestrial sites), SOFIA will observe at wavelengths from 0.3 μm through the sub-millimeter spectral region with an average transmission better than 80% (see Fig. 2). As such, SOFIA will allow observations in large parts of the spectrum that are completely inaccessible from the ground. Although some strong water absorption lines remain, the pressure broadening is much reduced so that high resolution spectroscopy is possible between these lines, enabling science observations at wavelengths heretofore only routinely observed with space-based platforms. The SOFIA aircraft, *Clipper Lindbergh*, will ordinarily be staged out of Palmdale, CA. However, it will be capable of operating from other bases, including several in the southern hemisphere, when necessary.

1.2. Special advantages of SOFIA

SOFIA is a near-space observatory that comes home after every flight. Its great strength is that science instruments can be adjusted, repaired (in flight if necessary) and exchanged regularly to accommodate changing science requirements and new technologies that do not have to

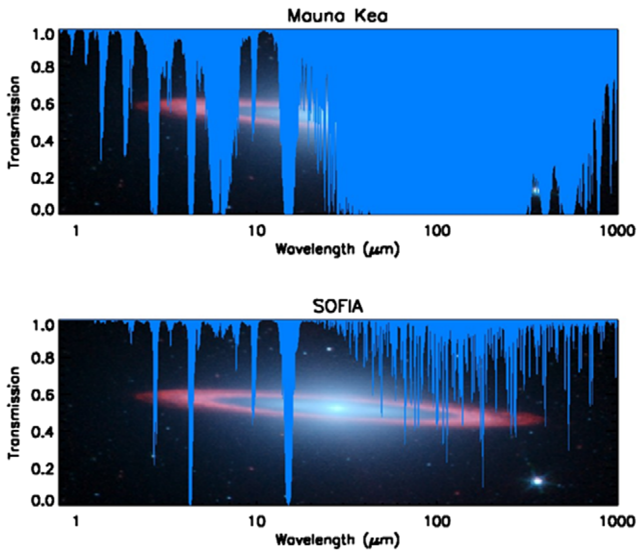


Fig. 2. The typical atmospheric transmission at a SOFIA observing altitude of 45,000 ft as compared to the transmission on a good night at Mauna Kea (13,800 ft, MSL). From 1 to 1000 μm, the average transmission is ⩾80% except in the center of absorption lines mostly due to mostly telluric H_2O. Background image: IRAC false color image of the Sombrero Galaxy, courtesy of NASA/JPL-Caltech.

await space qualification. Furthermore, large, massive, complex and sophisticated instruments with substantial power needs and heat dissipation can be flown on SOFIA. The portability of SOFIA is a unique and key enabling aspect of the mission. Since it can operate from other northern and southern hemisphere bases when necessary, it can conduct observations at any declination and respond promptly to targets of opportunity in any part of the sky. These include transient and location specific events such as variable stars, comets, occultations, eclipses novae and supernovae. SOFIA's lower elevation limit of 20 degrees will enable observations of important astrophysical events and solar system objects even when they occur close enough to the Sun to be unobservable from space missions. SOFIA's versatility will provide opportunities for observations at the forefront of science, and will give students the opportunity to participate in hands-on development of cutting edge instrumentation that would otherwise only be used in spacecraft applications. The continuous training of instrumentalists is a high priority for the United States science community. By virtue of this accessibility and the especially compelling venue, SOFIA will also include a vigorous, high visibility education and public outreach program.

2. The SOFIA Observatory and its instrumentation

We describe below and in Table 1 the NASA level 1 design and performance specifications of the SOFIA Observatory Facility, its initial complement of instruments, and the prospects for the development of future instrumentation.

Table 1
SOFIA system characteristics.

Characteristic	Value
Nominal operational wavelength	0.3–1600 μm
Primary mirror diameter	2.7 m
System clear aperture diameter	2.5 m
Nominal system *f*-ratio	*f*/19.6
Primary mirror *f*-ratio	*f*/1.28
Telescope's unvignetted elevation range	20–60 degrees
Unvignetted field-of-view	8 arcmin
Image quality of telescope optics at 0.6 μm	1.5 arcsec on-axis (80% encircled energy)
Diffraction-limited image size	0.1× (λ in μm) FWHM
Diffraction-limited wavelengths	⩾15 μm
Optical configuration	Bent Cassegrain with chopping secondary mirror and flat folding tertiary
Chopper frequencies	1–20 Hz for 2-point square wave chop
Maximum chop throw on the sky	±4 arcmin (unvignetted)
Pointing stability	1.0 arcsec RMS at first light; 0.2 arcsec RMS during full operations phase
Pointing accuracy	0.5 arcsec with on-axis focal plane tracking; 3 arcsec with on-axis fine-field tracking
Total emissivity of telescope (goal)	0.15 at 10 μm with dichroic tertiary; 0.1 at 10 μm with aluminized tertiary
Recovery air temperature in cavity (and optics temperature)	240 K

2.1. The SOFIA telescope and observatory

The SOFIA telescope (Fig. 3), supplied by DLR, is a bent Cassegrain with a 2.7 m (2.5 m effective aperture) parabolic primary mirror and a 0.35 m diameter hyperbolic secondary mirror. The telescope feeds two *f*/19.6 Nasmyth foci about 300 mm behind the instrument flange, the IR focus and a visible light focus for guiding, that are fed, respectively, by a gold coated dichroic and an aluminum coated flat. The secondary mirror provides chop amplitudes of up to ±5 arcmin between 0 and 20 Hz. The visible beam is fed into the Focal Plane Imager (FPI), an optical focal plane guiding system. Independent of the FPI there are two other optical imaging and guiding cameras available – a Fine Field Imager (FFI) and a Wide Field Imager (WFI). Both the FFI and WFI cameras are attached to the front ring of the telescope. These three guiding cameras represent increasingly large fields of view with decreasing pointing control accuracy. The telescope is in an open cavity in the aft section of the aircraft (Fig. 4) and views the sky through a port-side doorway that is opened at flight altitude. The telescope is articulated by magnetic torquers around a spherical support bearing through which the Nasmyth beam is passed. The focal plane instruments and the observers are on the pressurized side of the 21-ft diameter pressure bulkhead on which the bearing is mounted, allowing a shirt-sleeve working environment for the researchers and crew. The telescope has an unvignetted elevation range

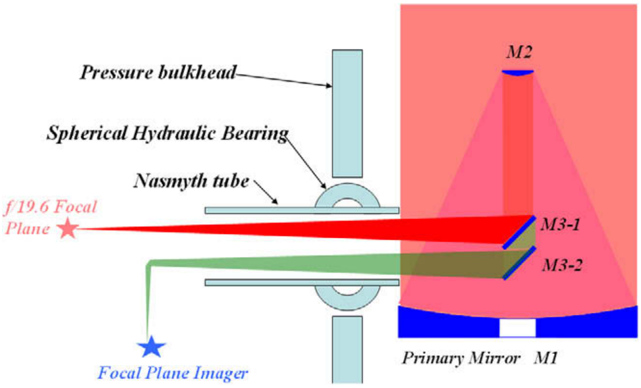


Fig. 3. The bent Cassegrain–Nasmyth optical configuration of the SOFIA 2.5-m infrared telescope (SOFIA Project Website, 2009).

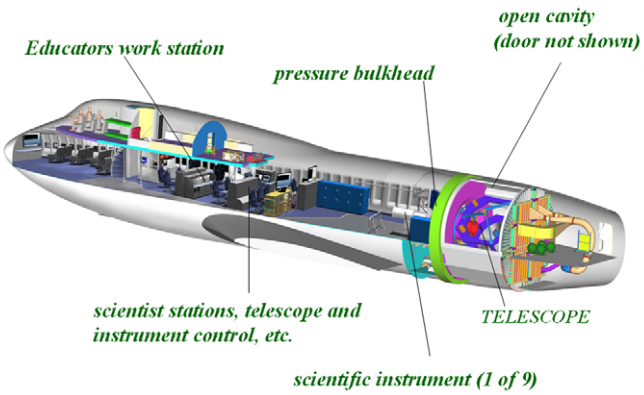


Fig. 4. A cut-away view of the SOFIA Observatory (SOFIA Project Website, 2009).

of 20–60 degrees. The cross-elevation travel is only ±3 degrees, so the airplane must be steered to provide this telescope movement. This latter requirement dictates that flight plans be developed to meet the science needs of each specific scientific observational program.

SOFIA's telescope optics have been designed to provide 1.5 arcsec images on-axis (80% encircled energy at 0.6 μm) so that diffraction-limited performance can eventually be expected at wavelengths longer than 15 μm. Pointing stability of the telescope will be 1.0 arcsec RMS at first light and is expected to be improved to 0.2 arcsec RMS during the full operations phase that begins in 2014. A pointing accuracy of 0.5 arcsec will be achievable with on-axis focal plane tracking.

Two factors motivated the aft installation of the telescope cavity instead of the scheme used in the KAO, where the cavity for the 0.76-m telescope was mounted ahead of the wing of the aircraft. First, only a single forward pressure bulkhead was required. Second, the numerous flight control systems operating the wing did not have to be diverted. Infrared images of the exhaust plumes of NASA's 747 Shuttle Carrier in flight and numerical simulations show that heat and turbulence from the port engine exhaust plumes will not significantly degrade telescope performance.

2.2. SOFIA's first-generation of instruments

Nine first-generation Science Instruments (SIs) are under development. In Table 2, we present the acronyms and full titles of the instruments, a summary of their basic capabilities, and information about the institutions and investigators involved in their development. These SIs cover a much wider range of wavelengths and spectral resolutions than the SIs of any other space observatory (see Fig. 5). These include three Facility Class Science Instruments (FSIs): HAWC, FORCAST, and FLITECAM. The US FSIs will be maintained and operated by the science staff of the SSMOC, and their pipeline-reduced and flux-calibrated data for selected modes will be archived at the SSMOC for access by the astronomical community after a one year proprietary period. Science users of FSIs will thus not need to have extensive knowledge or experience in infrared instrumentation or observing techniques. In addition, there are six Principle Investigator (PI) instruments maintained and operated by the individual PI teams. These instruments are designed to be less general in their potential applications than are the FSIs and are more likely to undergo upgrades between flight series. This has the advantage of keeping them more state-of-the-art at the expense of their needing recalibration after every configuration change. General Investigators (GI's) can propose to use these latter instruments in collaboration with the PI-team. Only raw data will be placed in the SOFIA data archive for the PI-class instruments. At the present time, it is expected that reduction software for data from PI-class instruments will be developed by the GI in collaboration with the PI-team. Two PI-class instruments are being developed in Germany, although the German PI instrument FIFI-LS will be available to the US science community as a facility-like instrument under special arrangement with the FIFI-LS team. The FIFI-LS data will be pipeline-reduced and flux-calibrated before it is placed in the data archive. We provide brief descriptions of the SOFIA first-light instruments below, starting with the two (FORCAST and GREAT) that will be available for Early Science.

2.2.1. FORCAST

FORCAST is a facility class, mid-infrared diffraction-limited camera with selectable filters for continuum imaging in two 4–25 μm and 25–40 μm bands, and also incorporates low resolution ($R = 200$–800) grism spectroscopy in the 4–8, 16–25 μm and/or 25–40 μm regions. It will provide the highest spatial resolutions possible with SOFIA, enabling detailed imaging of proto-stellar environments, young star clusters, molecular clouds, and galaxies. Simultaneous high-sensitivity wide-field imaging can be performed in the two-channels using 256 × 256 Si:As and Si:Sb detector arrays which sample at 0.75 arcsec/pixel giving a 3.2 arcmin × 3.2 arcmin field-of-view. For small objects, chopping can be performed on the array to increase sensitivity.

Table 2
SOFIA's first-light instrument complex.

Instrument	Description	Institution and PI	λ range (μm) Resolution ($\lambda/\Delta\lambda$)	Date available
FORCAST	*F*aint *O*bject Infra*R*ed *CA*mera for the *S*OFIA *T*elescope: facility instrument – mid-IR camera and grism spectrometer	Cornell University T. Herter	5–40 $R \sim 200$	2009
GREAT	*G*erman *RE*ceiver for *A*stronomy at *T*erahertz Frequencies: PI instrument – heterodyne spectrometer	MPIfR, KOSMA, DLR-WS R. Güsten	60–200 $R = 10^6$–10^8	2009
FIFI-LS	*F*ield *I*maging *F*ar-*I*nfrared *L*ine *S*pectrometer: PI instrument with facility-like capabilities – imaging grating spectrometer	MPE, Garching A. Poglitsch	42–210 $R = 1000$–3750	2009
FLITECAM	*F*irst *L*ight *I*nfrared *T*est *E*xperiment *CAM*era: facility instrument – near-IR test camera and grism spectrometer	UCLA I. McLean	1–5 $R \sim 2000$	2010
HIPO	*H*igh-speed *I*maging *P*hotometer for *O*ccultation: special PI instrument – high-speed imaging photometer	Lowell Observatory E. Dunham	0.3–1.1 R = UBVRI; custom NB filters	2010
HAWC	*H*igh-resolution *A*irborne *W*ideband *C*amera: facility instrument – far-IR bolometer camera	University of Chicago D. Harper	50–240 $R = 5$–10	2010
CASIMIR	*CA*ltech *S*ub-millimeter *I*nterstellar *M*edium *I*nvestigations *R*eciever: PI instrument – heterodyne spectrometer	Caltech J. Zmuidzinas	200–600 $R = 3 \times 10^4$–4×10^5	2010
EXES	Echelon-Cross-Echelle (*EXE*) *S*pectrograph: PI instrument – echelon spectrometer	University of Texas J. Lacy	5–28 $R = 10^4$, 10^5, or 3000	2012
SAFIRE	*S*ub-millimeter *A*nd *F*ar-*I*nfra*R*ed *E*xperiment: PI instrument – bolometer array spectrometer	GCFC H. Moseley	145–655 $R \sim 1000$	2012

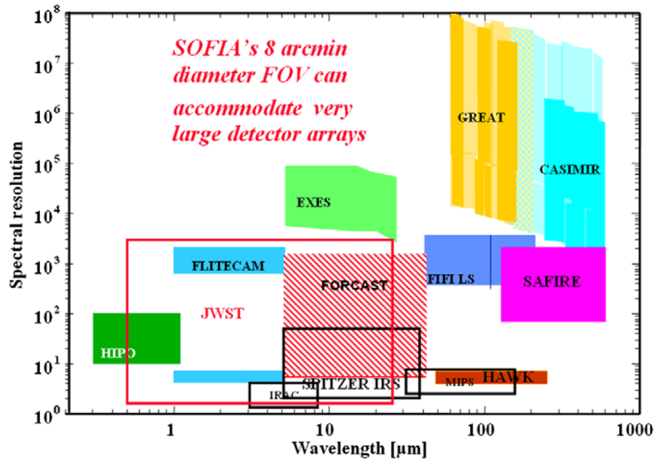


Fig. 5. SOFIA first-generation instruments shown in a plot of log spectral resolution vs. log wavelength. Black boxes are *Spitzer Space Telescope* Science Instruments (IRAC, IRS, and MIPS) for comparison. JWST (red box) will cover the 0.3–27 μm spectral region at resolutions as high as 3000. FORECAST and GREAT are the first-light instruments (SOFIA Project Website, 2009).

2.2.2. GREAT

GREAT, a PI-class instrument, will investigate a wide range of astronomical questions requiring the highest spectral resolution. These include observations of the 158 μm fine-structure transition of ionized carbon [CII], which is the most important cooling line of the cold interstellar medium and is a sensitive tracer of the star forming activity of a Galaxy. Observations of the 112 μm rotational ground-state transition of HD will allow the derivation of the abundance profile of deuterium across the Galactic disk and nearby galaxies, thereby providing unique information on the chemical evolution and star formation history of these systems. GREAT is a two-channel heterodyne instrument that offers observations in three frequency bands with frequency resolution down to 45 kHz (3.7×10^{-6} μm). The lower band, 1.4–1.9 THz (158–215 μm), covers fine-structure lines of ionized nitrogen and carbon. The middle band is centered on the cosmologically relevant 1–0 transition of deuterated molecular hydrogen (HD) at 2.6 THz (115 μm) and the rotational ground-state transition of OH. A high-frequency band includes the 63 μm transition of [O I]. The receivers employ sensitive superconducting mixer elements, SIS tunnel junctions and hot electron bolometers. A polarizing beam splitter allows simultaneous measurements of two lines the same time.

2.2.3. FIFI-LS

FIFI-LS, a PI-class instrument, is a unique tool for astronomical 3D spectral imaging of line emission in the far-infrared. This spectral region is largely unaffected by dust extinction and contains a large number of important fine-structure forbidden lines from ions such as [CII], which is a star formation tracer. The spectrometer contains two medium resolution ($R \sim 1700$) grating spectrometers with common fore-optics feeding two 16×25 pixel Ge:Ga detector arrays. A beam splitter allows the two Littrow spectrometers to undertake observations of an object in two spectral lines in the wavelength ranges 42–110 μm, and 110–210 μm, respectively, in first and second order An image slicer in each spectrometer redistributes 5×5

pixel diffraction-limited spatial fields-of-view along the 1×25 pixel entrance slits. FIFI-LS will offer instantaneous coverage over a velocity range of ~1500–3000 km/s around selected lines for each of the 25 spatial pixels.

2.2.4. FLITECAM

FLITECAM, a facility-class instrument, will provide seeing-limited imaging from 1–3 μm and diffraction-limited imaging from 3 to 5.2 μm. FLITECAM will also provide moderate resolution grism spectroscopy ($R \sim 2000$) from 1 to 5.2 μm. Its objective is to cover science applications motivated by good atmospheric transmission and low thermal background characteristic of SOFIA's flight environment. It will be especially useful for studying the distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in HII regions, the interstellar medium (ISM), proto-stellar clouds, planetary nebulae, and galaxies with high levels of star formation. FLITECAM will be used in the early stages of SOFIA operations to evaluate the SOFIA telescope assembly imaging and infrared background quality. FLITECAM can operate together with the Special Class Instrument HIPO (High-speed Imaging Photometer for Occultation) on SOFIA for simultaneous measurements of the same object in the sky.

2.2.5. HIPO

HIPO is a special-purpose PI-class instrument designed to provide simultaneous high-speed, time-resolved imaging photometry at two optical wavelengths. HIPO makes use of SOFIA's mobility and freedom from clouds to provide data on transient events like occultations and transits of extra-solar planets. HIPO and FLITECAM can be mounted simultaneously to enable data acquisition at two optical and one near-IR wavelength. HIPO has a flexible optical system and numerous readout modes, allowing specialized observations.

2.2.6. HAWC

HAWC is a facility-class far-infrared camera intended to provide high spatial resolution, broad-band imaging capability at wavelengths of 50–240 μm and spectral resolutions of $R = 5$–10 to reveal the energetics and morphology of dust enshrouded sources and to aid our understanding of the physics and chemistry of the interstellar medium. It utilizes a 12×32 pixel array of bolometer detectors constructed using the silicon pop-up detector (SPUD) technology developed at Goddard Space Flight Center. The array will be cooled by an adiabatic demagnetization refrigerator and operated at a temperature of 0.2 K. Plans to upgrade HAWC to perform far-infrared polarimetry are currently being pursued.

2.2.7. CASIMIR

CASIMIR is a PI-class sub-millimeter and far-infrared heterodyne receiver that will be used to study far-infrared line emission related to the evolution of galaxies and the birth and death of stars. The instrument uses sensitive superconducting mixers, including both tunnel junction (SIS) and eventually hot electron bolometers (HEB). The local oscillators are continuously tunable. CASIMIR will cover the 500–2100 GHz frequency range (143–600 μm) in seven bands: SIS mixers in four bands up to 1200 GHz (250 μm), and HEB mixers in three bands covering the rest. Four bands can be selected for use on a given flight. The receiver has an intermediate-frequency (IF) bandwidth of 4 GHz, processed by a high resolution backend acousto-optic spectrometer with 1 MHz resolution and a low resolution (30 MHz) analog correlator.

2.2.8. EXES

EXES is a PI-class instrument designed to study line emission from molecular hydrogen, water vapor, and methane from sources such as molecular clouds, protoplanetary disks, interstellar shocks, circumstellar shells, and planetary atmospheres. The instrument operates in three spectroscopic modes ($R \sim 10^5$, 10^4, and 3000) from 5–28 μm using a 256×256 Si:As BIB detector. High dispersion is provided by a large echelon grating. This requires an echelle grating to cross-disperse the spectrum, resulting in continuous wavelength coverage over a bandwidth of ~1% of the central wavelength and a slit length of ~10″ at $R = 10^5$. The echelon can be bypassed so that the echelle or low order grating acts as the sole dispersive element. This results in a single order spectrum with slit length of roughly 90″ and a selectable spectral resolution of $R = 10^4$ or 3000, respectively. The low resolution grating also serves as a slit positioning camera when used face on.

2.2.9. SAFIRE

SAFIRE is a PI-class imaging spectrometer covering the spectral region from 145 to 655 μm with a spectral resolving power of about 1000. It will be used for imaging of interstellar, circumstellar, and Galactic environments in molecular and atomic lines to gain into the physical processes at work in stellar and Galactic evolution. The instrument uses a 32×32 arrays of bolometers to provide background limited performance for critical science applications. The nominal field-of-view is about 5.3 arcmin.

2.3. SOFIA's performance specifications with its first-generation instruments

SOFIA will observe at wavelengths from 0.3 μm to submillimeter wavelengths and with its first-generation instruments will be capable of high resolution spectroscopy ($R > 10^4$) at selected wavelengths between 5 and 600 μm (see Fig. 5). Its 8 arcmin diameter field-of-view (FOV) is compatible with the use of very large format detector arrays. Despite the relatively large thermal IR background compared to that associated with cryogenic space missions, the 2.5-m aperture of the SOFIA telescope will enable measurements with about an order of magnitude better sensitivity and a factor of >5 better linear spatial resolution than The *Infrared Astronomical Satellite* (IRAS, Neugebauer et al.,

1984) and will match or be more sensitive than the *Infrared Space Observatory* (ISO, Kessler et al., 1996) at high spectral resolution (Fig. 6, upper left). In addition, the spectral resolution offered will be far higher than that currently available with *Spitzer*. With its capability for diffraction-limited imaging beyond 25 μm, SOFIA will give the sharpest images of any current or planned IR telescope operating in the 30–60 μm region (Fig. 6, upper right).

2.4. Future instrumentation development for SOFIA

The advantage of an airborne observatory over space-based missions to rapidly incorporate instrument improvements and upgrades in response to new technological developments will be a cornerstone of SOFIA. Technology is still expanding rapidly in the far-IR and major advances in sensitivity and array size are expected. Advances expected to occur during SOFIA's lifetime were recently explored at a workshop entitled "SOFIA's 2020 Vision: Scientific and Technological Opportunities," held at Caltech during December 6–8, 2007 (Young et al., 2008). The SOFIA Project will support a technology development program that will regularly provide such opportunities. The next call for new instruments will be in FY 2010. There will be additional calls every 3 years resulting in one new instrument or major upgrade to the observatory instrumentation each year. Possible future capability based on this work and the 2020 Vision Workshop includes:

- Expanded Heterodyne Wavelength coverage to enable more complete chemical studies of the interstellar medium.
- Arrays of Heterodyne Detectors to increase in observing speed and spectral mapping at high velocity resolution.

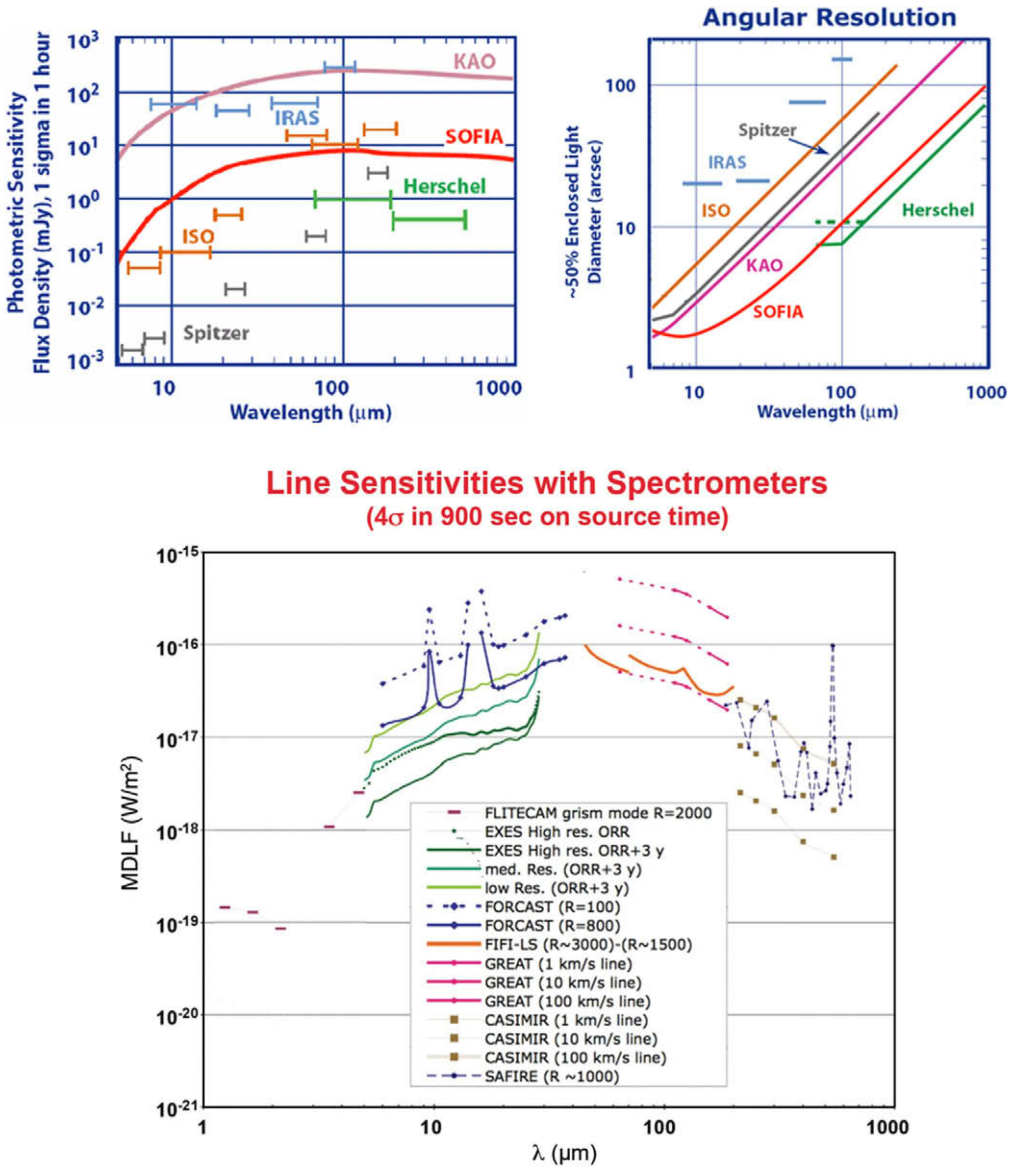


Fig. 6. SOFIA's photometric sensitivity will be comparable to that of ISO (upper left). It will form images three times smaller than those formed by the *Spitzer Space Telescope* (upper right). Spectral sensitivities are shown in the lower panel (SOFIA Project Website, 2009).

- Polarimeters to probe the structure of magnetic fields in interstellar clouds.
- $R \sim 2000$, 5–60 μm Integral Field Unit Spectrometer to facilitate studies of the ISM on Galactic scales.
- A variety of new spectrometers designed to facilitate detailed studies of the physics and chemistry of interstellar, circumstellar, and Galactic environments.

3. Synergy between SOFIA and other missions

The comparative performance of SOFIA with respect to other infrared missions has been noted in Section 2.3 above. In addition, no space-based mission is presently envisioned with a spectral resolution exceeding 3000 in the 3–150 μm range, the "home" 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. In the sub-sections below we compare and contrast SOFIA's science potential with those of concurrent facilities. SOFIA science will complement and exploit the availability of data from other existing facilities such as HST, *Chandra*, *Spitzer*, future facilities such as WISE, *Herschel*, JWST, ALMA, and SAFIR (see Fig. 7), and offer synergies with large scale optical/infrared ground-based surveys such as *Visible and Infrared Survey Telescope for Astronomy* (VISTA; McPherson et al., 2003), the *Panoramic Survey Telescope and Rapid Response System* (Pan-STARRS; Kaiser et al., 2002) and *Large Synoptic Survey Telescope* (LSST; Tyson, 2002), as well as support for targets of large ground-based telescopes such as ALMA, and eventually *Giant Segmented Mirror Telescopes* (GSMTs; Kan and Antebi, 2003).

3.1. SOFIA and Hubble Space Telescope

The Hubble Space Telescope (HST; Burrows et al., 1991), with its complement of detectors, has IR capabilities shortward of 2.4 μm. HST works at the diffraction limit of the telescope (2.5 m), and has unprecedented sensitivity. SOFIA complements HST: it extends the wavelength range out into the sub-millimeter wavelength range, and has a higher spectral resolution at near-infrared wavelengths. With SOFIA one can therefore extend star formation work by directly viewing the youngest stars deep inside the molecular clouds out of which they are born, and studying the chemistry and dynamics of the clouds that produce them. The relationship between the young stars seen by HST and the processes within the natal clouds from which they are emerging is a key to our understanding of star formation.

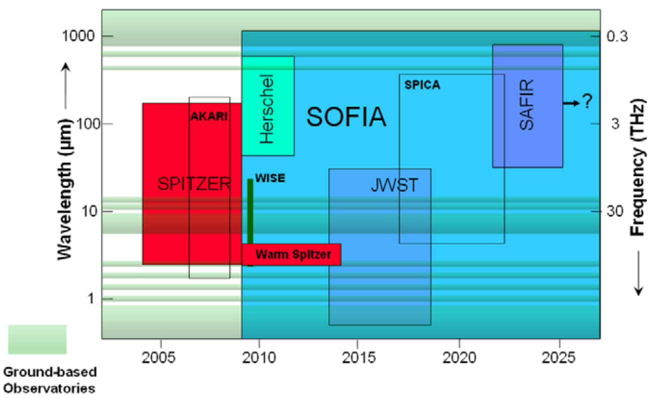


Fig. 7. SOFIA's flight lifetime and time-frame will make it the premier facility for doing far-IR and sub-millimeter wave astronomy from 2010 until the mid 2030s. It will be the only facility available for wavelength coverage in the 28–1200 μm spectral region and for high resolution spectroscopy during most of that period. The SPICA and SAFIR missions have yet to be formally approved. The length of the SAFIR mission is undetermined at present (SOFIA Project Website, 2009).

3.2. SOFIA and JWST

SOFIA is very complementary to JWST (Gardner et al., 2006). Before JWST is deployed and after *Spitzer* cryogens run out, SOFIA is only mission with capabilities from 5 to 8 μm, a spectral region crucial for the investigation of important organic signatures. Intense 6.2 and 7.7 μm aromatic bands have been especially relevant to the atomic structure of these complex hydrocarbons. After JWST is launched, SOFIA is the only mission to give complementary observation beyond 28 μm and high resolution spectroscopy in the 5–28 μm region. This high resolution spectroscopy will provide important probes of fine-structure line emission that characterize interstellar gas clouds. For infrared studies of comets, in which the hydrocarbon chemistry is of principal significance to that of the early Earth, SOFIA can observe these objects as they track into the inner solar system, where the ices sublimate and this chemistry is best revealed.

3.3. SOFIA and Herschel

Herschel (Pilbratt, 2003) and SOFIA will now begin their missions at about the same time, and joint calibration work is ongoing. During the years that these missions overlap, SOFIA will be only program (see Fig. 8) with 25–60 μm capability and with high resolution spectroscopy in the 60–150 μm region. When *Herschel*'s cryogens are depleted in ~2012, SOFIA will be the only NASA mission with 25–600 μm capabilities for many years. Important follow-up of *Herschel* discoveries can be made with SOFIA. Advanced instrumentation will give unique capabilities to SOFIA that will complement *Herschel*. These include polarimetry and heterodyne arrays (see Fig. 8). The 25–60 μm spectral region is of special significance for understanding the thermal structure of star forming clouds, as the Wien slope of the spectral energy distribution is seen here. This spectral region is also fundamentally important for distinguishing the properties of large hydrocarbon (e.g., PAH) grains.

3.4. SOFIA and Spitzer

SOFIA will become operational near the time that the *Spitzer Space Telescope* (Werner et al., 2004; Gehrz et al.,

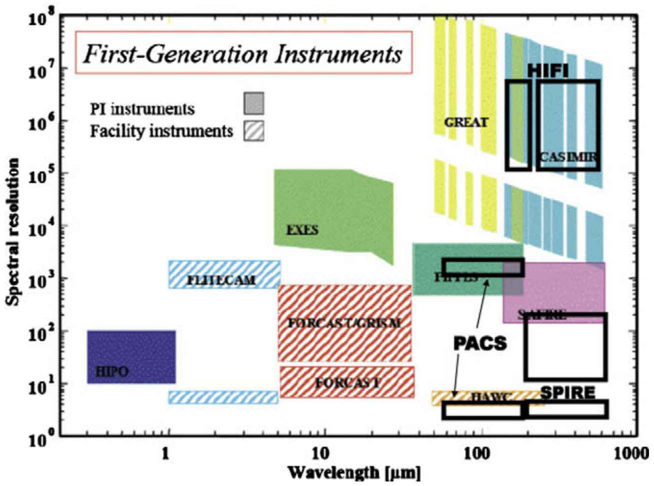


Fig. 8. A comparison of the SOFIA first-generation Science Instrument and the *Herschel* Science Instrument complements (SOFIA Project Website, 2009).

2007) runs out of cryogens. *Spitzer* is a high-sensitivity imaging and low resolution spectroscopy mission. SOFIA is a high spectral and high angular resolution mission. Many of the discoveries of *Spitzer*, especially from the Legacy Program surveys, will be followed up with SOFIA's high resolution imaging and spectroscopy. The high resolution from SOFIA will be essential for probing the chemistry and motions within the Galactic star forming clouds that *Spitzer* observations highlighted. The high-sensitivity of *Spitzer* has led to identification of young, rapidly star forming galaxies at high red shift. The resolution of SOFIA will allow astronomers to examine the details of such starburst processes in nearby galaxies, such that the systematics of these can inform the studies of the more distant ones.

3.5. SOFIA and WISE

The *Wide-Field Infrared Survey Explorer* (WISE; Liu et al., 2008) is a very sensitive 3.3–23 μm all sky survey that will be launched just as SOFIA begins operations. SOFIA can provide a number of important follow-up observations. Very red sources seen only at 23 μm can be followed up at 38 μm with FORCAST on SOFIA and spectra can be obtained with EXES on SOFIA for the brightest 23 μm sources. Nearby cold Brown Dwarfs discovered by WISE can be followed up spectroscopically with the FLITECAM grisms and with EXES.

3.6. SOFIA and AKARI

The Japanese AKARI (Formerly ASTRO-F, Shibai, 2007) mission has instrumental capabilities that bear on SOFIA. Even in its current warm mission phase, which presents no lifetime limits, AKARI will have the ability to do near-infrared imaging and low resolution pointed spectroscopy. The SOFIA FLITECAM instrument has similar sensitivity, but offers higher spatial resolution, and a flexible filter set.

3.7. SOFIA and Planck

Two years after its 2009 launch, *Planck* (Tauber, 2004) will issue an 350–1500 μm all sky Early Release Compact Source Catalog with 5 arcmin resolution and a sensitivity (10 sigma) in the 1 Jy range. Many new discoveries will come from this survey. Almost all will need follow-up observations. SOFIA will be well placed in time and instrumentation to make important follow-up of these discoveries because it will have much higher angular resolution, can make many observations at shorter frequencies, and will have spectrometers with various resolutions.

3.8. SOFIA and the Chandra X-ray Observatory

NASA has explored 15-year lifetime options for the *Chandra X-ray Observatory* (CXO, *Chandra*; Weisskopf et al., 2000) that would have the observatory operational until 2014. As such *Chandra* and SOFIA could be operational simultaneously. X-ray astronomy and infrared astronomy, while far apart in photon energies, is that they share the ability to penetrate and see things embedded within obscuring dust clouds. For example, *Chandra* and SOFIA will have important complementary in elucidating how the remnant disks confine the flows around proto-stars deeply embedded in star forming regions.

3.9. SOFIA and large OIR ground-based telescopes

Large OIR ground-based telescopes can outperform SOFIA as far as spatial resolution is concerned. In particular, 8–10 m telescopes such as *Gemini* (Roche, 2001), VLT (Merkle and Schneermann, 1986), Keck (Nelson, 1989), or *Large Binocular Telescope* (LBT; Hill, 1997) equipped with laser guide stars and adaptive optics, can achieve spatial resolutions of 0.05–0.10 arcsec in the near-infrared. Also, the diffraction limit of 8–10 m telescopes at mid- and far-infrared wavelengths is higher by a factor of 3–4 than that of SOFIA. However, the thermal background is much lower for SOFIA, and SOFIA can operate in the key wavelength ranges of 5–8 μm, 13–15 μm, and beyond 22 μm where Earth's atmosphere is essentially opaque for ground-based observatories. We further note that SOFIA and *Gemini* have similar sensitivity for point sources at 20 μm, but SOFIA is much faster for wide-field mapping with FORCAST. Future larger ground-based GSMTs such as *Giant Magellan Telescope* (GMT; Johns, 2004), *Thirty Meter Telescope* (TMT; Nelson, 2008), and the *European Extremely Large Telescope* (E-ELT; Monnet, 2007) will extend the capabilities represented by *Gemini*, but just in very finite atmospheric windows.

3.10. SOFIA and ALMA

When the *Atacama Large Millimeter Array* (ALMA; Brown et al., 2004) comes on line at its highest frequency of 850 GHz (350 μm), it will have very high angular resolution (<0.1 arcsec) and good sensitivity. The higher frequencies accessible on SOFIA will play a major role in the tracing of light atoms and molecules through ground-state transitions in the clouds that ALMA will see at higher resolution.

3.11. SOFIA and other missions

While SOFIA is strongly complementary to large NASA investments, as described above, it also has strong synergies with *Kepler* (Koch et al., 2006), which will identify extra-solar planetary eclipsing systems for which the very low scintillation noise with SOFIA will provide opportunities for follow-up and more detailed analysis. Future efforts on large far-infrared space missions such as the *Single Aperture Far-Infrared* (SAFIR) *Observatory* (Benford et al., 2004) will depend on technologies pioneered on SOFIA.

4. Science opportunities with SOFIA

SOFIA observations will support NASA's Astrophysics Strategic Plan. The mid- and far-IR wavelength regions are keys to studies of the dusty universe. SOFIA science emphasizes four major themes: (1) the contents of our solar system and extra-solar planetary systems, (2) the interstellar medium as the origin of the materials that are the building blocks of life and planets, (3) star and planet formation and stellar evolution, and (4) the center of our Galaxy and star formation in a Galactic context through observations of nearby galaxies.

Many of the most interesting objects in the universe are hidden from view by dense layers of obscuring dust and gas. These include such diverse objects as black holes in the centers of galaxies, and budding stars and planetary systems. Information on these objects and their astrophysical workings must be gleaned from their interaction with their environment. In essence, the obscuring dust and gas "down converts" energetic photons from embedded objects into IR and sub-millimeter lines and continuum radiation. SOFIA, with its diverse complement of instruments, is uniquely suited to study deeply embedded objects and to determine their role in the evolution of galaxies. We illustrate in Fig. 9 how SOFIA, with its broad range of wavelength and spectral resolution coverage, will be able to attack a diverse array of science investigations. Below, we discuss in more detail some topics associated with SOFIA's key science themes from a contemporary perspective.

4.1. The minerals and ices in comet comae and tails

Comets agglomerated from proto-solar nebular condensates beyond the ice line where insolation and thermal pro-

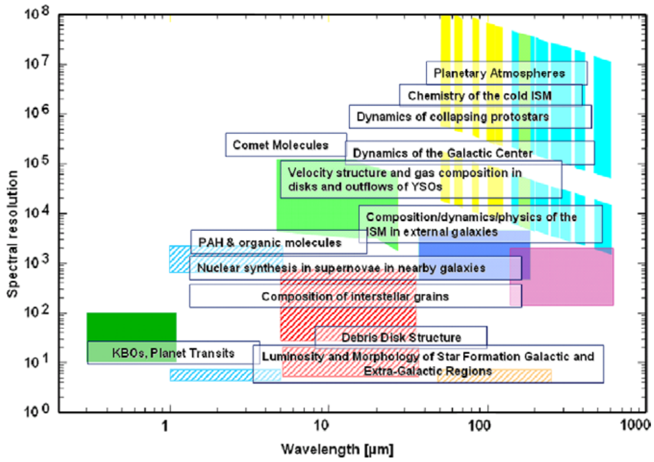


Fig. 9. The same plot as in Fig. 5 with the science topics overlaid in the appropriate positions for the SOFIA first-generation Science Instruments (SOFIA Project Website, 2009).

cessing is minimal. They are likely the most pristine objects in our solar system, because their small size has prevented them from undergoing internal processing since their formation. As such, they contain key information about the physical and chemical conditions of our early solar system. To gain a better understanding of the make-up of these bodies, NASA and ESA have sent spacecraft to a limited sample of comets. *Giotto* flew by comet Halley in 1986 and was followed two decades later by the *Deep Impact*, *Stardust*, and *Rosetta* missions to other comets. However, since comets are a very diverse group of bodies, further comprehensive observations of both dynamically new and periodic comets are required to ascertain which models of solar system formation are relevant. Particular examples of questions remaining to be answered are: What are the differences between the dynamically new comets from the Oort cloud, and the Jupiter family comets from the Kuiper Belt? Was there a common nursery for both comet families, or did they form in different regions?

Since cometary nuclei are enshrouded in a cloud of gas and dust, they cannot usually be probed directly. However, IR and sub-millimeter spectroscopy enable observations of the so-called "parent molecules" that sublime directly off the nucleus, and hence contain direct information on the composition of the nucleus. Production rates of volatiles are used to quantify cometary activity and to measure volatile abundances. The sub-millimeter wavelength region, accessible to SOFIA, enables the detection of CHN bearing molecules (e.g., HCN, H_2CO) that can be used to determine key isotopic ratios in the gaseous component of comets. Water (H_2O) is the dominant ice in cometary nuclei and its sublimation governs the activity of comets at heliocentric distances, $\leqslant$3 AU from the Sun. Water production rates, the rotational temperature, and the nuclear spin temperature inferred from the water ortho-to-para ratio are physical parameters useful in a variety of studies related to cometary atmospheres and cometary physics, and help characterize the place of origin for different comets (e.g., Bockelée-Morvan et al., 2009). Unlike other constituents of cometary atmospheres, water vapor is difficult to observe directly from the ground because telluric absorption. Non-resonance fluorescence vibrational bands (hot bands) not absorbed by telluric water can be observed from the ground in relatively active comets with water production rates greater than a few times 10^{28} molecules s^{-1} (Disanti and Mumma, 2008). The detection of the water fundamental vibrational bands at 2.7 μm and 6.3 μm and rotational lines in the sub-millimeter and far-infrared domains, requires SOFIA or space-based instrumentation (Woodward et al., 2007). Of particular interest are SOFIA observations in the 6–7 μm band (EXES), inaccessible from the ground, that enable measurement of the spin temperature (ortho-to-para ratio) of water in many comets. It is thought that the spin temperature of the water in the ices may reflect the temperature of the grains on which these ices formed.

SOFIA will be an outstanding platform for studying the mineralogy of comet dust grains. The 5–45 μm spectral region contains the signatures of amorphous carbon and silicate grains as well as a number of resonance emission features from crystalline silicates, such as forsterite (Mg-rich crystalline olivine), which has features between 10 μm and 33 μm (Fig. 10). The high atmospheric opacity beyond 13 μm makes ground-based telescopes largely unsuitable for much of this analysis.

Such spectroscopic data on materials in the comae, tails, and trails of comets provide ground truth for our understanding of how materials in circumstellar shells, the ISM, the interplanetary medium, and asteroids are related. With SOFIA data, it is possible to make comparisons between the physical, chemical, and mineral composition of the materials in Inter-planetary Dust Particles (IDPs), meteorites, *Stardust* in circumstellar winds, and in the debris disks of young stars.

Spitzer will not be operational for mid-IR spectroscopy after mid-2009, and it cannot observe objects along sight lines closer than 1 AU to the Sun. Because comets are brightest when they are physically close to the Sun, most comets cannot be observed with *Spitzer* when they are at the peak of their activity near perihelion passage. The same restriction also applies to both *Herschel* and JWST. This restriction also prevents observations by these space platforms when the comets are at opposition, when they are often closest to the observatory, and have the best spatial resolution in km.

4.2. Exploring the Kuiper Belt with stellar occultations

Although Pluto and many other newly defined dwarf planets in and beyond the Kuiper Belt may not be as pristine objects as smaller objects, they do contain key information on how the population of these bodies formed and evolved. Hence, knowledge of their fundamental properties is essential to our understanding of the origin and early evolution of the outer solar system. In addition to conventional imaging and spectroscopic observations, stellar occultations are a unique attribute of SOFIA to investigate dwarf planets in detail. Such occultations provide a spatial resolution of a few kilometers (Elliot and Dunham, 2005). From such data we can establish their diameters, detect or place limits on their atmospheres, and search for potential nearby companions. The small zones of visibility of occultations on Earth and the faintness of most occulted stars make occultations difficult to observe from deployable ground-based observatories. A large, mobile telescope like SOFIA that can fly into the shadow of an occultation (see Fig. 11a) has access to a factor of nearly a hundred more occultations than can be observed each year from the ground. SOFIA observations of ten stellar occultations of the four brightest potential dwarf planets can be done with HIPO and FLITECAM over the first several years of operations. Searches for residual atmospheres and their properties around other small bodies in the outer solar system will be a major goal of SOFIA. Such targets would include planetary satellites as well. We note that the atmosphere of Pluto was discovered during a stellar occultation observed by Elliot et al. (1989) with the KAO. The inversion of the KAO light curve (Fig. 11b) shows that Pluto's atmosphere has an extended isothermal zone atop a steep low altitude inversion layer. Significant seasonal variations and structures interpreted as atmospheric waves have been identified in Pluto's atmosphere during subsequent stellar occultations many years after the KAO observations, suggesting that extended follow-up with the large aperture and long temporal baseline of SOFIA will be scientifically productive (Sicardy et al., 2003; Person et al., 2008; McCarthy et al., 2008).

4.3. Planetary atmospheres

With the discovery of an ever growing number of planets in other stellar systems (exo-planets), the atmospheres of planets in our own solar system have become increasingly important as laboratories for exo-planet research. The large obliquities of Saturn (and its moon, Titan), Uranus, and Neptune lead to large seasonal variations in temperature and photochemistry. Neptune's appearance has changed drastically between 1989 (the year of the Voyager flyby) and the early 21st century, as Neptune approaches summer solstice in its southern hemisphere. Spectra of Neptune at mid-infrared wavelengths showed large changes, in particular in the ethane emission band. SOFIA can make long-term observations throughout the mid-infrared at wavelengths that are mostly unobservable from the ground, covering emission bands of a variety of hydrocarbons and of the collision-induced S(0) and S(1) molecular hydrogen lines, sensitive to atmospheric temperature. Such SOFIA observations are essential to determine whether the changes seen on Neptune are indeed seasonal or if there is an alternative explanation. On the larger planets Jupiter and Saturn, such emissions can be mapped with FORCAST across their disks, providing additional information on potential seasonal variations.

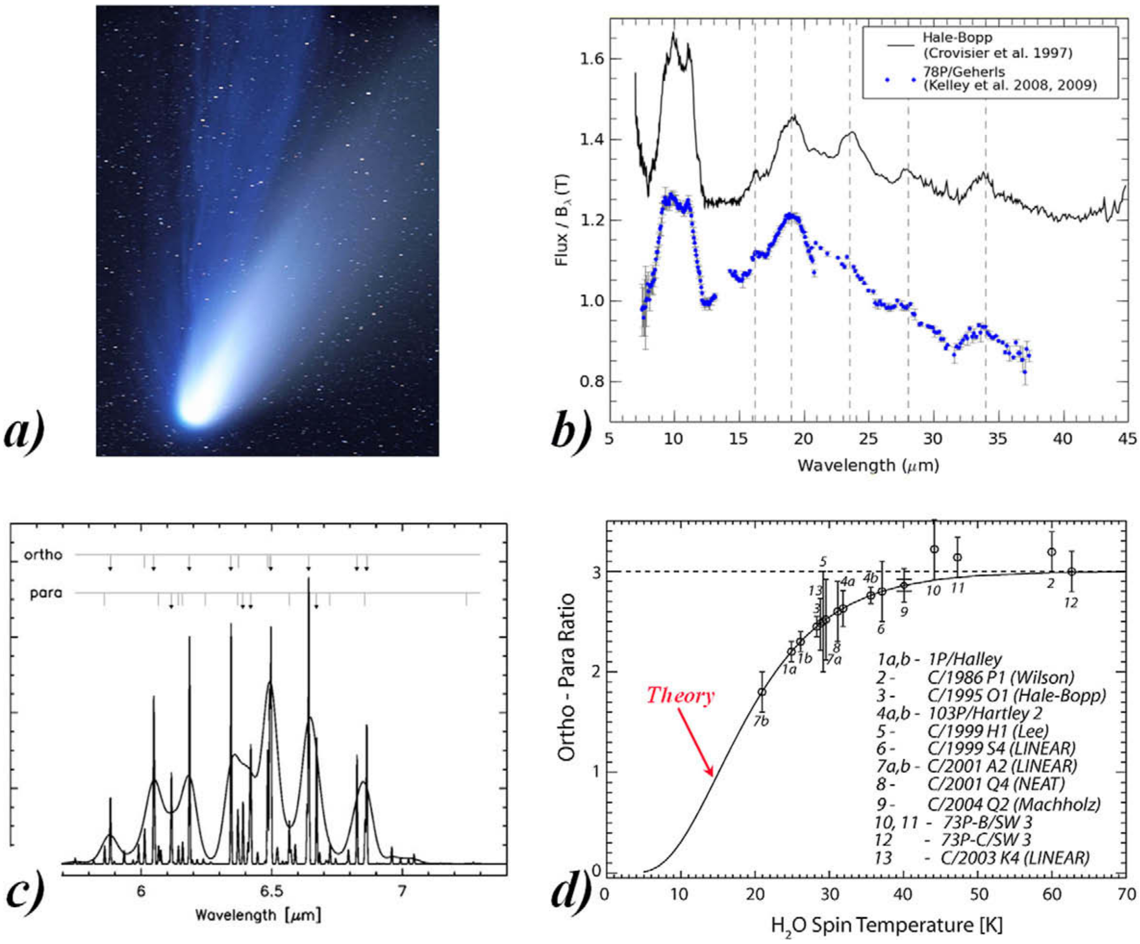


Fig. 10. IR spectra of comet comae and tails (a) show the different features available in the 1–35 μm spectral region for the study of comet grain mineralogy (b) and the emission from gas-phase constituents such as water (c), whose ortho/para ratio (d) can be used to deduced conditions under which the comet nucleus formed. (a) Photograph by John Gleason; (b) data from Crovisier et al. (1997) and Kelley et al. (2008, 2009); (c) Woodward et al. (2007); (d) Bonev et al. (2007). SOFIA will offer unique opportunities to study these objects.

SOFIA observations of Venus have the potential to be very useful. Due to some unfortunate instrumentation failures, recent Venus probe spacecraft have not provided the anticipated high spectral resolution atmospheric data. Unlike missions such as *Spitzer* and JWST, SOFIA can look closer to the Sun and does not saturate on bright objects. Both capabilities are needed to observe Venus.

4.4. Precise photometry of extra-solar planet transits

SOFIA will fly above most of the scintillating component of the Earth's atmosphere and may yield very precise and stable photometric measurements of stars. While the capability has yet to be proven, we anticipate that very high quality data on transits of extra-solar planets can be obtained with SOFIA using HIPO and FLITECAM (see Fig. 12), at least as a stretch goal. Precise photometric observations of transiting extra-solar planets can, in principle, provide a wealth of data on the physical properties of these objects. Planetary radius, orbital inclination, stellar limb darkening, evidence for planetary satellites or rings, and atmospheric composition can be found from the transit observation alone. Combined with high quality radial velocity data, the mass and density of the planet can be determined. Perturbations by other planets in the system can be found by variations in transit timing over a period of years. Initially, work with SOFIA will focus on the two or three brightest known transiting planets. The ongoing spectroscopic programs designed specifically to find objects bright enough for detailed follow-up work are expected to add numerous extra-solar planets to this list over SOFIA's lifetime (Dunham et al., 2005).

4.5. Nucleosynthesis in classical nova explosions

The astrophysical thermo-nuclear runaways that produce classical nova explosions may play an important part in producing some of the isotopic anomalies that are present in the meteoritic and cometary debris that represent the remains of the primitive solar system (Fig. 13). Gehrz (2008) has reviewed the use of IR observations to quantify the physical parameters of classical nova outbursts and to

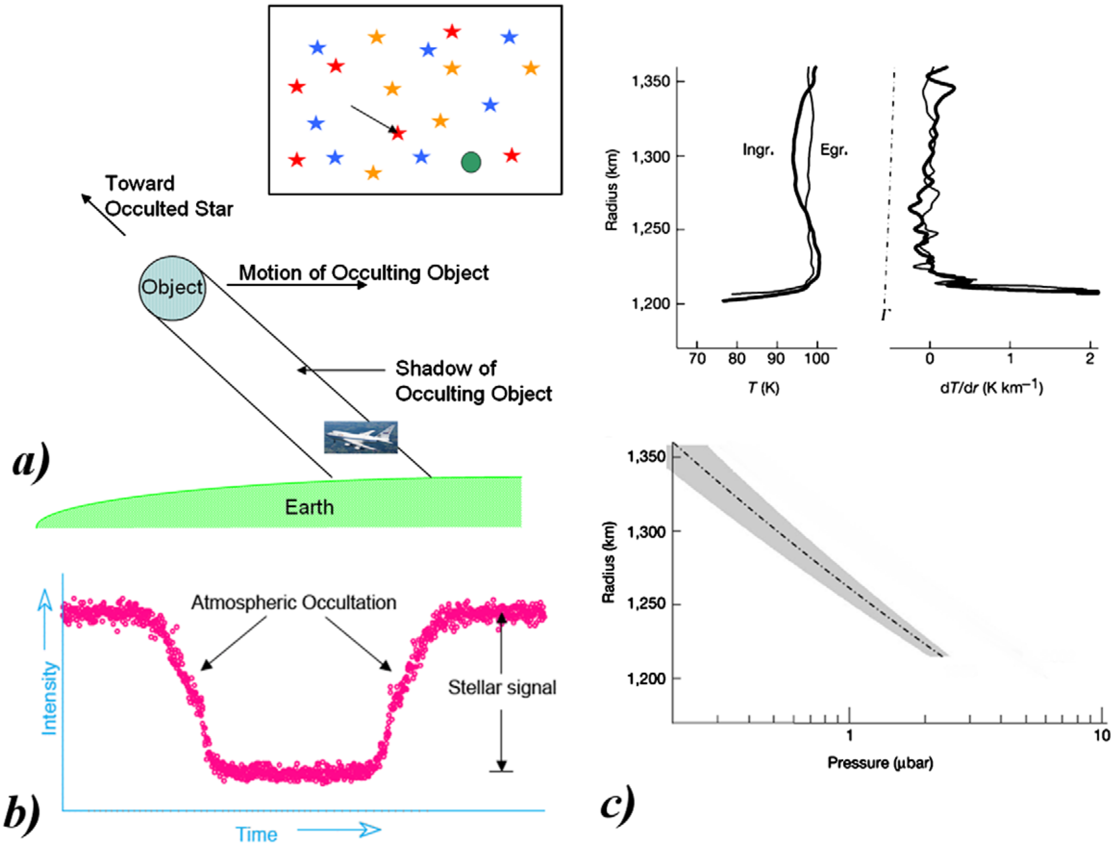


Fig. 11. Occultation studies with SOFIA will probe the sizes, atmospheres, and possible satellites of newly discovered planet-like objects in the outer solar system. (a) SOFIA can fly directly into the shadow of an occultation, making available hundreds of events per year compared to the handful accessible with ground-based observatories. (b) Pluto occultation light curve observed on the KAO (1988) probes the atmosphere. Data from Elliot et al. (1989). (c) The inversion of the occultation light curve using a spherically symmetric nitrogen atmosphere model shows that Pluto's atmosphere is essentially isothermal with a strong low level inversion layer. Modified figure from Sicardy et al. (2003).

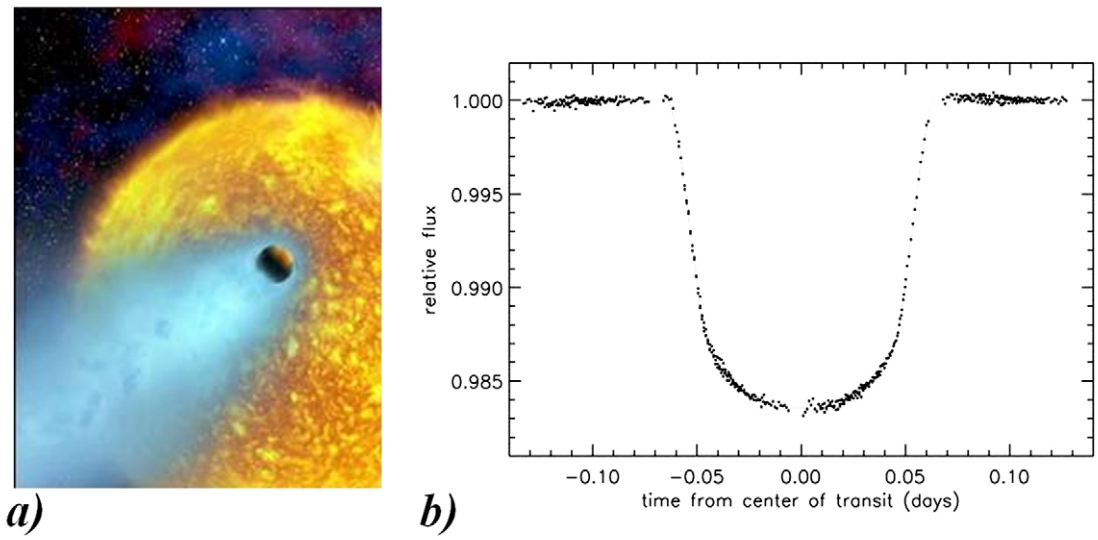


Fig. 12. SOFIA, flying above the scintillating component of the atmosphere, will be the most sensitive freely pointing observatory for extra-solar planetary transits after HST. Above are an artist's concept (a) and HST STIS data (b) showing the transit of a large extra-solar planet transiting across the face of its star, HD 209458. NASA images.

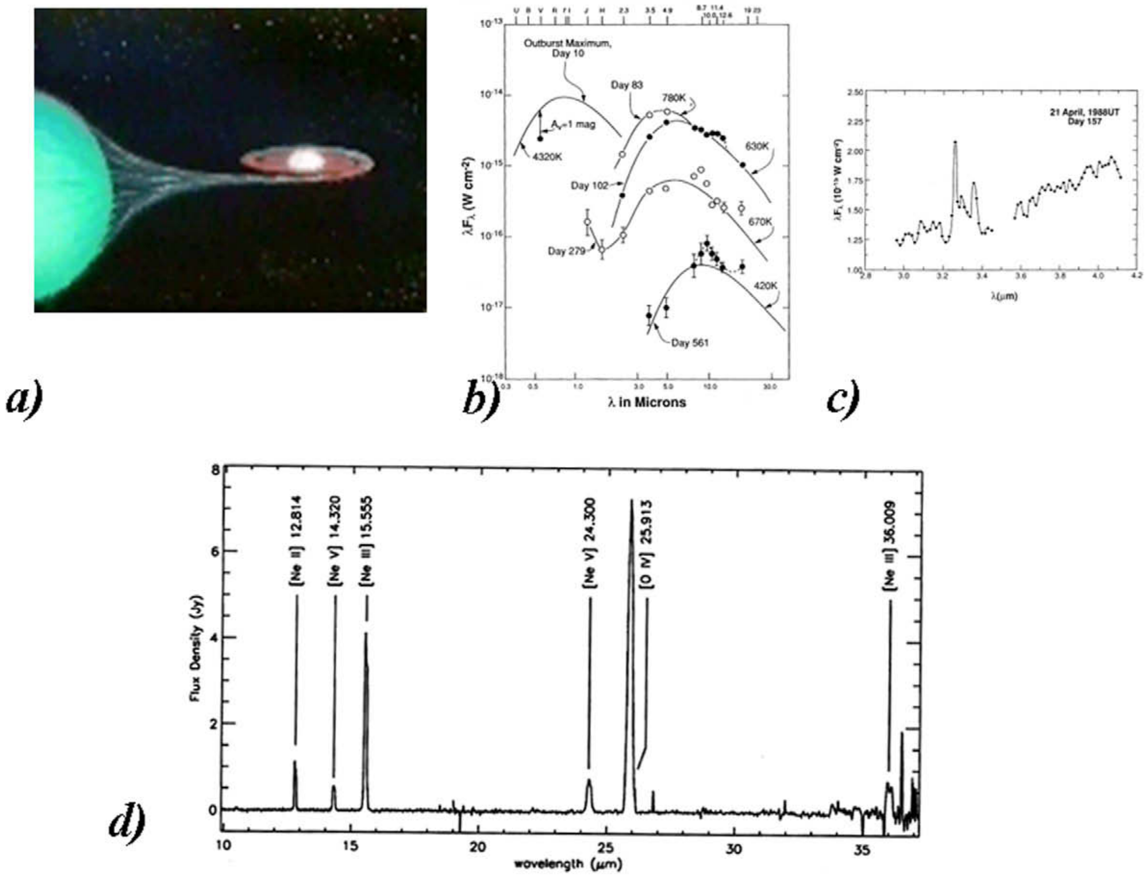


Fig. 13. SOFIA will provide new insights into nova explosions caused by thermo-nuclear runaways on the surfaces of white dwarfs accreting matter in close binary systems (a) lead to the production carbon, silicate, and SiC mineral grains (b), hydrocarbon grains (c), and a rich abundance of gas-phase metals such as Ne and O in *Spitzer Space Spectra* (d). Abundances and kinematics can be determined from the spectra. (a) from R. Narayan et al. (CfA), ASCA, ISAS, NASA; data in (b) and (c) from Gehrz et al. (1992), (d) from Gehrz (2008).

assess their contribution to the chemical abundances in the ISM where star formation occurs. Solid phase and gas phase abundances in nova ejecta can be deduced from IR dust emission features and IR forbidden emission lines from highly ionized metals. These observations can provide basic information about the thermo-nuclear runaway (TNR) that causes the nova explosion, the chemical composition of the white dwarf (WD) upon which the TNR occurs, and the nature of the WD's progenitor star. Recent IR observations with ground-based telescopes and the *Spitzer Space Telescope* have shown that some recent bright novae ejected shells were extremely overabundant in CNO, Ne, Mg, Al, and Si. These observations have also demonstrated that the physical properties and mineralogy of dust produced by novae are similar to those of the small grains released from comet nuclei.

SOFIA will be a superb platform for observing nova explosions on several counts. First, its mobility will enable the timely monitoring of the temporal development of nova events. This requires observational capabilities that cover all possible declinations and the capability of following events that develop on time-scales of days, weeks, and months, and even as the object approaches the solar line-of-sight. Second, the spectroscopic capabilities of SOFIA will enable the recording of many forbidden lines obscured by the atmosphere from ground-based observatories and unavailable to the spectrometers of other space missions. An assessment of the strengths of these lines is necessary to determine accurate elemental abundances in nova ejecta. Third, high resolution spectroscopy of these lines will provide a powerful probe of the physical conditions (e.g., density and temperature), ionization state, energetics, mass, and kinematics of the ejected gas through studies of the atomic fine-structure lines of [O I] (63 and 145 μm), [O III] (52, 88 μm), [O IV] (25.9 μm), [C II] (158 μm), [S I] (26 μm), [Si II] (34 μm), and [S III] (18.7 μm). In addition, numerous forbidden lines of neon, an indicator of progenitor mass and white-dwarf type, lie in obscured atmospheric bands that are available to SOFIA.

4.6. Water in planet-forming disks

Angular momentum conservation during the collapse phase will cause proto-stars to be surrounded by circumstellar (CS) gaseous disks (Shu et al., 1987) that are natural sites for planet formation. It is generally believed that water (H_2O) plays a major role in the formation and early evolution of planetary systems, and SOFIA can be a major asset in understanding it. Water is the dominant reservoir of oxygen under nebular conditions so that water ice condensation will dominate the mass budget of newly-formed planetesimals. It is thought that the cores of giant planets are formed beyond the "snow line", the boundary in a disk where the temperature falls below the 170 K sublimation temperature of water ice (Sasselov and Lecar, 2000). The origin and distribution of water in the inner proto-planetary disks is crucial to our understanding of the abundance of water on terrestrial planets in the habitable zones around stars (see Watson et al., 2007 and Fig. 14).

Previous observational studies of planet-forming systems have focused exclusively on the mid-IR thermal continuum emission from dust in the disk because detection of molecular emission lines of water from the gas phase is difficult with present instrumentation (Mundy et al., 2000). EXES, designed for high resolution spectroscopy of ro-vibrational transitions of water in the mid-IR, will be uniquely suited to study the distribution of water in the disks around young proto-stars. These lines, which are caused by pumping by stellar photons, are expected to be in emission for face-on disks and in absorption against the stellar photosphere for highly inclined disks. The strength of the lines will provide direct measurements of the temperature and column density of water in these disks.

While the spatial resolution of SOFIA will be limited, the resolved line profile provides, in combination with *Kepler*'s law, will yield the distribution of the water in the emitting layers of the disk. Observations of water lines in the 2.0–2.4 μm window have revealed the power of such molecular line studies, but these short wavelength lines are from very hot gas close to the proto-star. The 6 μm region, on the other hand, is sensitive to the warm gas in the terrestrial planet zone and near the snow line. We note that studies of the pure rotational lines at sub-millimeter wavelengths are hampered by either severe beam dilution or by telluric absorption.

4.7. Star formation and the interstellar medium of galaxies

The interstellar medium (ISM) plays a central role in the evolution of galaxies as both the birth site of new stars and the repository for old stellar ejecta. This is shown schematically in Fig. 15. The formation of new stars slowly con-

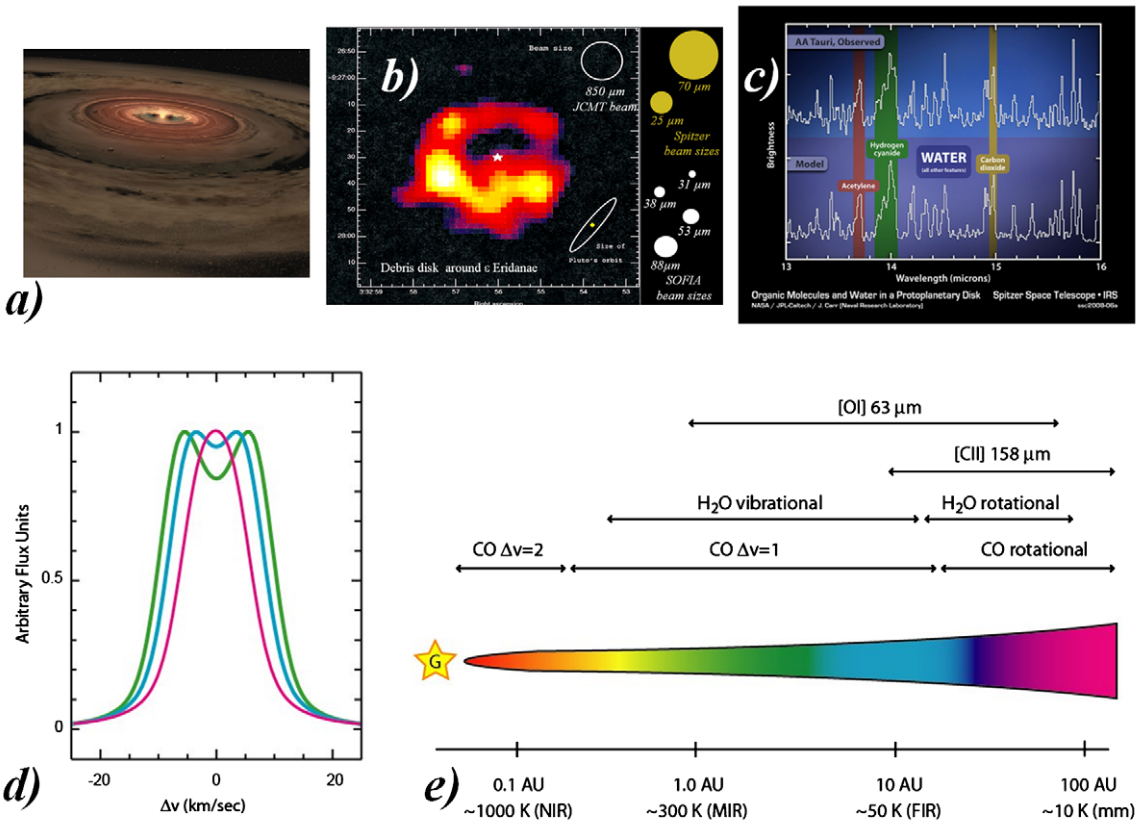


Fig. 14. SOFIA will play a key role in the study of water and organic molecules in proto-planetary disks. Artist's conception of a young star encircled by a proto-planetary disk (a), the resolved debris disk of ε Eridani showing that SOFIA's beams can resolve considerable spatial detail (b), and NASA *Spitzer Space Telescope* spectra of a proto-planetary disk revealing the signatures of H_2O vapor, CO_2, HCN, and acetylene – some of the basic building blocks of life (c). All from NASA/JPL-Caltech/J. Carr, NRL. Line shapes (d) and lines in various IR wavelength regimes (e) can reveal physical conditions in the disk. The physical locations of the various atomic and molecular constituents of the disk in (e) were estimated with the help of chemical models presented by Kamp and Dullemond (2004). (a) NASA/JPL-Caltech, image in (b) JAC/UCLA and Royal Observatory, Edinburgh; (c) NASA/JPL-Caltech/Naval Research Laboratory; (d and e) Evans et al. (2009).

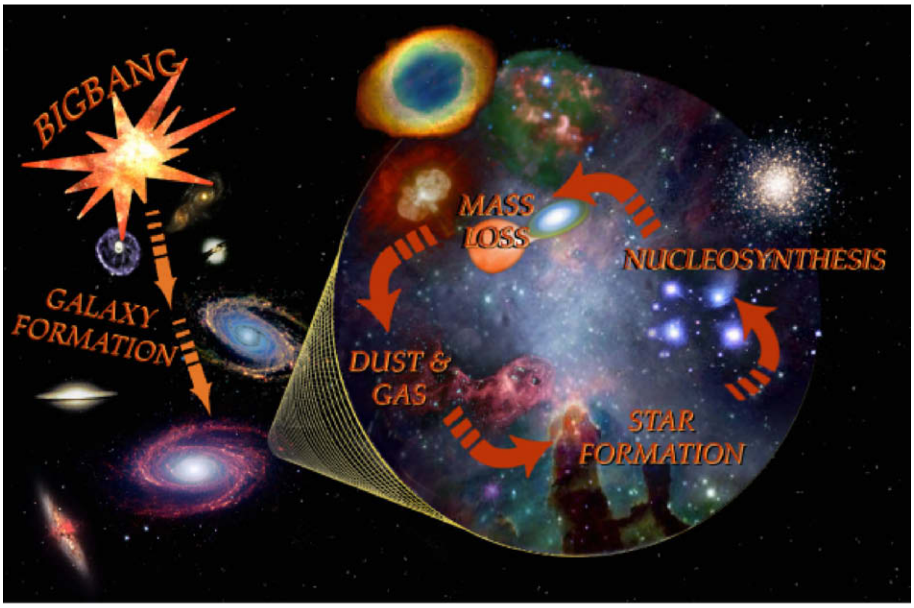


Fig. 15. Chemical evolution of the universe. After Gehrz (2008).

sumes 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), novae, and supernovae inject products of stellar and explosive nucleosynthesis into the ISM, slowly increasing its metallicity. This constant recycling and the associated enrichment drive the evolution of a Galaxy's visible matter and changes its emission characteristics. To understand this recycling, we must study the physical processes of the ISM, star formation, mass-loss from evolved stars, and their relationships on a Galactic scale. Dust and gas play a major role in these processes. SOFIA with its wide wavelength coverage and high spectral resolution capabilities is destined to play a dominant role in this field.

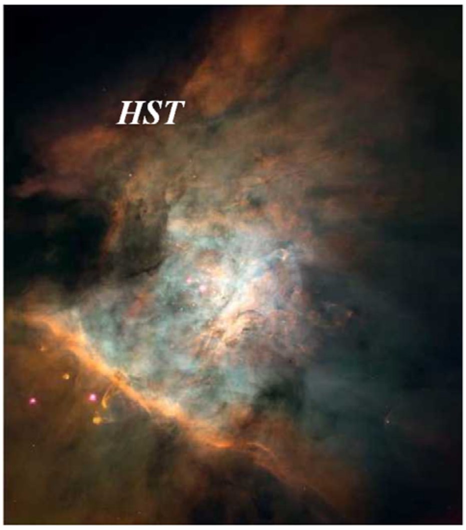
SOFIA instruments will provide high spatial and spectral resolution studies of the energy distributions of active regions of star formation (see Fig. 16) and known stellar death sites such as supernova remnants, planetary nebulae, AGB stars, and RSG stars. Follow-up studies with SOFIA's moderate and high resolution spectrometers will probe the detailed composition of the gas and dust. Together, these data will allow astronomers to derive the density, temperature, chemical, and luminosity structure of these regions. Of specific importance are the atomic fine-structure lines of [O I] (63 and 145 μm) and of [C II] (158 μm). These lines are bright in regions illuminated or shocked by the outflows of massive stars and supernova explosions. The GREAT instrument on SOFIA will be the only means to resolve these lines at the sub-km/s level and probe in detail the physical conditions in these regions and their kinematics.

Polarization measurements with SOFIA will make important contributions to our understanding of the way in which magnetic fields determine the evolution of proto-stellar objects in massive star forming regions. Polarization measurements with HAWC (see Section 2.2.3) in the FIR will probe warm, dense material in the dense cores of these massive regions (see Fig. 17).

A particularly relevant example of how IR spectra can be used to study the star formation process in external galaxies is shown in Fig. 18. Here, low-resolution *Spitzer Space Telescope* IRS spectra toward a sample of deeply obscured nuclei of ultra-luminous infrared galaxies show vibration-rotational molecular absorption bands revealing the presence of dense, warm molecular gas with column densities ranging from a few 10^{15} to $10^{17}\,\mathrm{cm}^{-2}$. Lahuis et al. (2007) have suggested that the warm dense molecular gas causing these mid-IR absorption lines may be associated with star formation in a region where extreme physical conditions inhibit the expansion of HII regions and the star formation process is therefore physically confined in an "extended" hot-core phase. High resolution spectroscopic observations of the brightest galaxies in this sample with SOFIA might be expected to provide dynamical information to test this hypothesis.

4.8. The interstellar deuterium abundance

Deuterium in the universe was created in the Big Bang and the primordial deuterium abundance provides the best constraint on the mass density of baryons in the universe. Its abundance provides strong constraints on the physical conditions during the first few minutes of the universe's expansion. However, this record of the Big Bang has been subsequently modified by stellar nuclear burning as material has been cycled from stars to the ISM and back to stars by the cycle of stellar evolution (see Fig. 15). Deuterium is destroyed in most stellar burning scenarios. Deuterium is thus potentially a key element the star formation history of the universe. As pointed out by Neufeld et al. (2006),



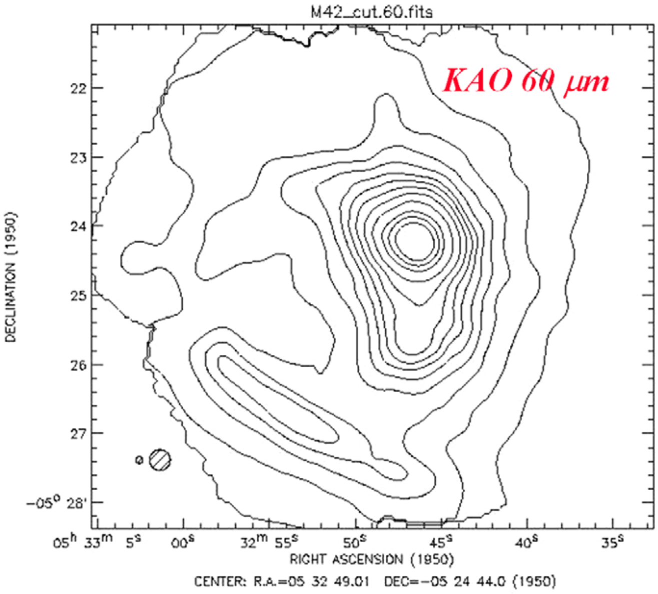


Fig. 16. HST image of the Orion Nebula (left) compared with a 60 μm map of the same area made with the KAO (right). With 9 SOFIA beams for every 1 KAO beam (red box), SOFIA imagers/HI-RES spectrometers can analyze the physics and chemistry of individual proto-stellar condensations seen by HST and *Herschel* where they emit most of their energy and can follow-up on *Herschel* discoveries (SOFIA Project Website, 2009).

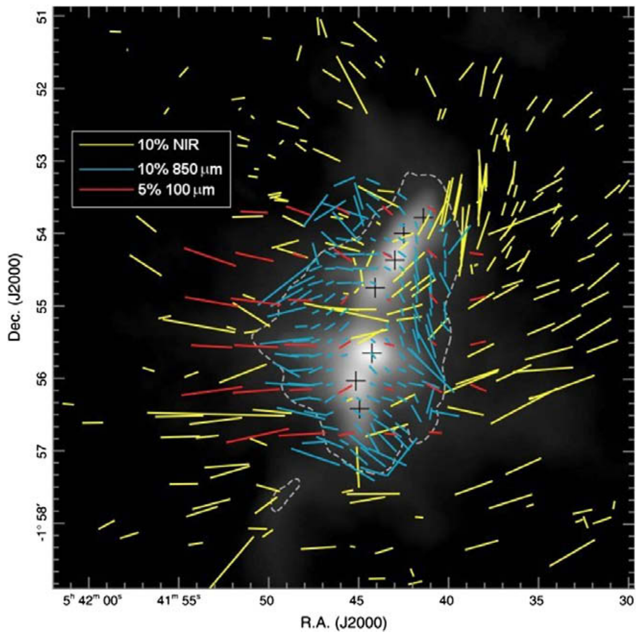


Fig. 17. Magnetic field distribution in the massive star forming cloud NGC 2024. Within the dashed contour, the NIR and sub-millimeter polarizations disagree on field direction. The NIR does not probe the warm, dense material that is probed by the FIR measurements. IRSF/SIRIUS and JCMT/SCUBA data from Kandori et al. (2007).

hydrogen deuteride (HD) is a proxy for the cold molecular hydrogen component of the ISM in the Galaxy, and the distribution of deuterium in the Galaxy thus probes both stellar processing and the efficiency with which the debris of stellar evolution is mixed into the interstellar medium. HD has a much lower excitation temperature than molecular hydrogen and a much higher dipole moment that compensates the line strength for the much higher abundance of molecular hydrogen.

Measuring the amount of cold HD ($T < 50$ K) and therefore the deuterium abundance throughout our Galaxy can best be done by observing the 112 μm ground-state rotational transition line of HD with SOFIA (Fig. 19). The 3 THz (100 μm) channel on the SOFIA GREAT instrument is designed to measure this line at sub-km/s resolution. HD will be seen in emission in the warm gas associated with photo-dissociation 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 destruction by nuclear burning in stars throughout the Galaxy. There is no other observatory with the appropriate wavelength coverage and spectral resolution required for this study (Güsten, 2005). In the future, HD mapping could be used to map out the cold molecular gas component of galaxies much in the way 21 cm mapping is used to map out the neutral hydrogen (HI) component.

4.9. The black hole and circumnuclear disk at the Galactic Center

A $4 \times 10^6 M_{\odot}$ black hole has been shown to exist in the heavily obscured core of the Milky Way (Ghez et al., 2000; Genzel et al., 2000). SOFIA's first-light instruments will be very well suited to study the material falling into this black hole and make observations of the emission from the circumnuclear disk region surrounding it.

The circumnuclear disk (CND, Fig. 20) orbiting the super-massive black hole at the Galactic Center at a distance of 1–5 parsecs holds the key to understanding the

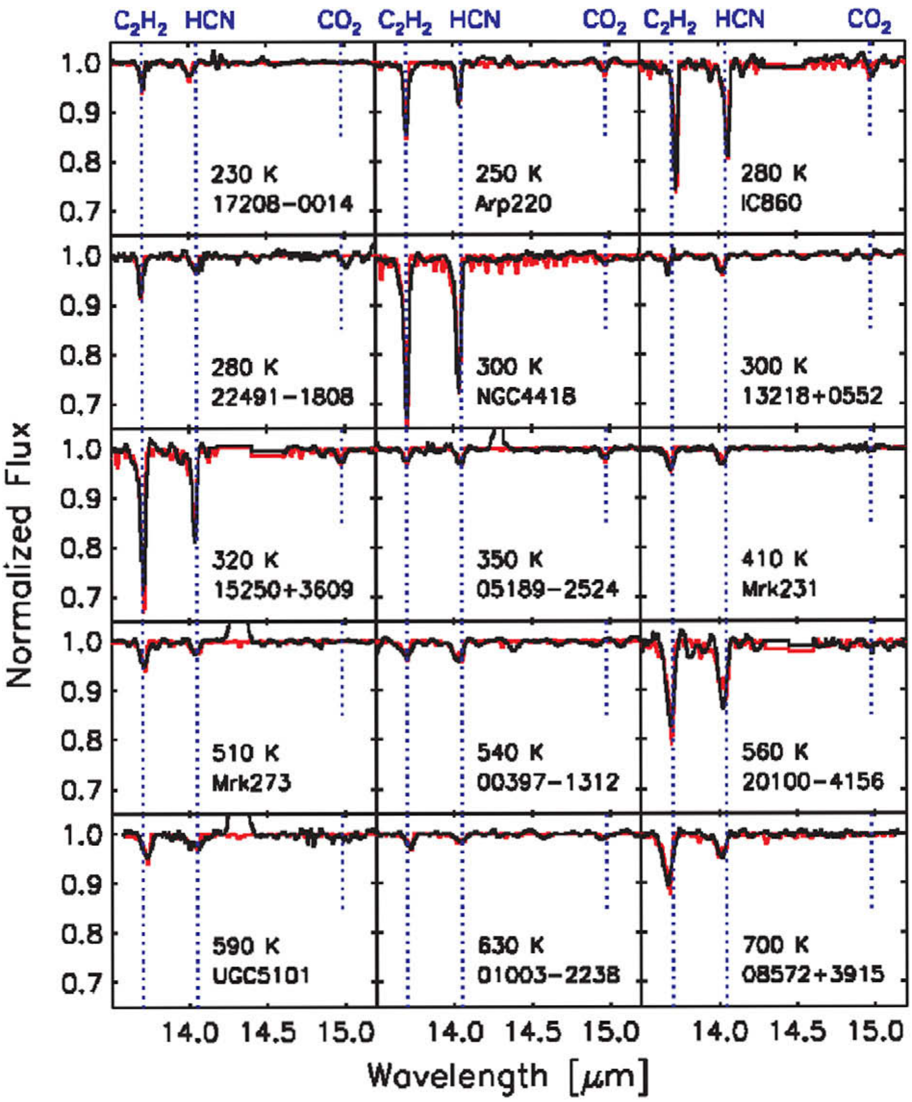


Fig. 18. Continuum divided *Spitzer Space Telescope* IRS spectra of a sample of ultra-luminous infrared galaxies showing the absorption bands of C_2H_2 and HCN and some of CO_2. Plotted in red are best-fit spectra assuming a single excitation temperature for all three molecules. All spectra have been shifted to rest wavelengths (Lahuis et al., 2007). SOFIA will provide broad spectral coverage and key measurements of the active nucleus and star forming environment in many of these luminous objects.

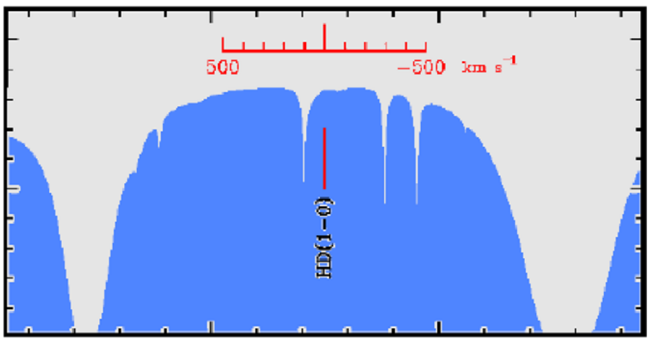


Fig. 19. Schematic representation of the atmospheric transmission (*Y* axis) around the 112 μm HD line at a SOFIA observing altitude of 40,000 ft showing that there is a relatively transparent window about 2000 km s^{-1} wide centered on the rest wavelength of the line (SOFIA Project Website, 2009).

long-term activity of this unique region in our Galaxy. This torus of dust and gas constitutes a reservoir of material that can fuel a violent episode of accretion activity and might be responsible for the star formation evidenced by the cluster of massive stars occupying the central parsec. Strong mid and far-IR radiation emerges from the CND, so it is ideally suited for study by several instruments on SOFIA (Morris et al., 2005). For example, high resolution spectroscopy using EXES, FIFI-LS, GREAT, and CASIMIR will provide a powerful probe of the physical conditions (e.g., density and temperature), ionization state, energetics, mass, and kinematics of the gas through studies of the pure rotational H2 lines, the atomic fine-structure lines of [O I] (63 and 145 μm), [O III] (52, 88 μm), [O IV] (25.9 μm), [C II] (158 μm), [Si II] (34 μm), and [S I] (26 μm) and [S III] (18.7 μm), and high level rotational levels of CO (e.g., $J = 14–13$).

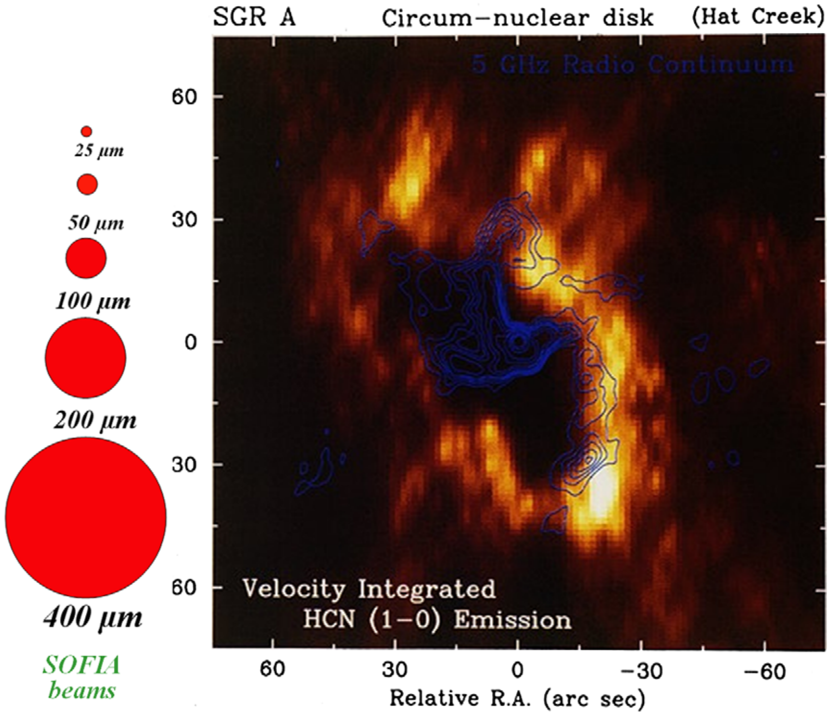


Fig. 20. SOFIA imagers and spectrometers can resolve detailed structures in the Galactic circumnuclear disk to reveal the physical, chemical, and dynamical properties of the material that feeds the massive black hole at the Galactic Center (SOFIA Project Website, 2009).

5. Summary

The Stratospheric Observatory for IR Astronomy (SOFIA) will be the premier platform from which to make many imaging and spectroscopic astronomical observations in the IR and sub-millimeter spectral regions for the next twenty years. With its access to obscured regions of the atmosphere, its rapid and global deployability, and its ability to deploy new and updated instruments, SOFIA will play an important role in a variety of astrophysical problems well into the first third of the 21st century.

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