The 20/20 Vision of SOFIA:
Scientific and Technical Opportunities in the next 20 years

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Abstract

The SOFIA 2020 Vision Workshop explored the technical and scientific opportunities for the SOFIA observatory for the next two decades. More than 120 scientists attended the workshop and discussed future directions in instrumentation and astronomy. The participants found that long term success of the facility depended on a vigorous instrumentation program, and that the new instrumentation offered potentially many new investigations. The general trend in instruments depended on the development of very large format far-infrared direct detection and heterodyne arrays. It was emphasized that for a significant period time (after Herschel and before a large space mission like SPICA or SAFIR), SOFIA will be the only access to much of the key far-infrared and sub-millimeter wavelength range.

I. Introduction

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a cooperative effort between NASA and the German Aerospace Center (DLR) to develop and operate an airborne astronomical observatory optimized for infrared and sub-millimeter wavelengths. The facility will feature a 2.5-m clear aperture telescope installed in a modified Boeing 747SP aircraft and have an stable of instruments supporting observations throughout its primary 3 μm to 1.6 mm wavelength range.

With a planned 20-year operational lifetime, SOFIA will likely see many great changes in both the science and the technology of the field. During the planned SOFIA operational period, major new capabilities such as Herschel, JWST, and ALMA will be in use, while others like SPICA and SAFIR are in the conceptual phases. How does SOFIA fit in with all these new capabilities? What are some of the anticipated instrumental developments that could maintain SOFIA's ability to do forefront science? What are some of the new investigations that will be enabled by these capabilities?

In that context, Caltech, USRA, NASA, and DLR sponsored the SOFIA 2020 Vision Workshop at Caltech on December 6-7, 2007. The Symposium was organized by Eric Becklin (USRA), Alexandre Karpov (Caltech), Tom Phillips (Caltech), and Jonas Zmuidzinas (Caltech) with the assistance of the Scientific Organizing Committee listed in Appendix A. The goal of the workshop was to bring together both astronomers and technologists to identify some of the important opportunities and directions for the facility over the next 20 years. More than 120 scientists attended over the two days, with intermixed sessions of astrophysics and instrumentation. This White Paper was written to gather together some of the key themes that were identified at the Workshop. It cannot, however, capture the full breadth of the presentations, and the interested reader is referred to the conference web site where most of the talks are available.

http://www.sofia-vision.caltech.edu/program.html

In addition to the formal presentations and posters, the Workshop also conducted breakout sessions with the participants to develop consensus views on key instrumental needs for different areas of astronomy. Sessions were held on Instrumentation, Galaxies, Galactic Star formation, and the Solar System.

II. Capabilities of the Facility

The basic capabilities of SOFIA are determined by the size of the telescope (2.5 m), the field of view (up to 12'), the image quality (diffraction-limited beyond 25 μm), and the infrared background. The infrared background, which is driven by emission of the telescope and the atmosphere, determines the ultimate sensitivity of SOFIA in most cases. Additional contributions to the noise can come from atmospheric fluctuations associated with flight.

The basic capabilities of SOFIA are summarized in Figures 1 and 2. In raw sensitivity and angular resolution, SOFIA will be roughly comparable to Herschel. As warm facilities, both will be background noise limited for photometric observations. The power of SOFIA ultimately will come from advancements in instrumentation, and many possibilities were discussed during the workshop. Finally, in terms of capabilities, it is important to remember that except for a few atmospheric windows, ***SOFIA will be the only facility to provide regular access to the 25 μm – 1200 μm wavelength range during the next decade.***

III. Current Status of SOFIA

2007 was an eventful year for SOFIA. After a very long development period, SOFIA took its first flight on April 26, 2007, and it was subsequently ferried to NASA Dryden Flight Research Center one month later.

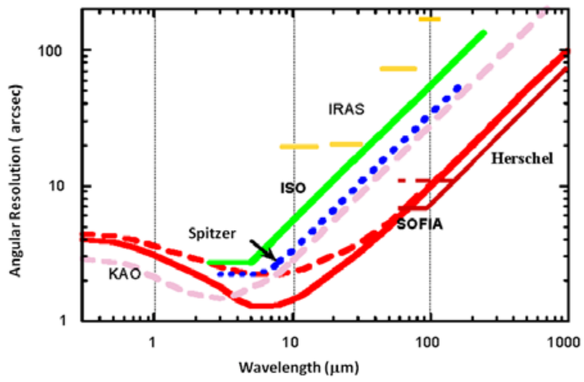

Figure 1 Angular resolution of SOFIA compared with past and existing facilities. Ground-based observations are possible in the atmospheric windows.

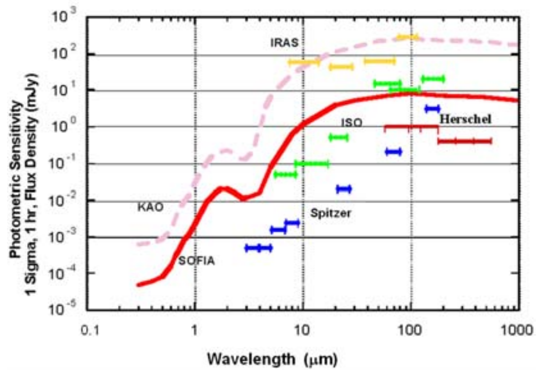

Figure 2 Projected photometric sensitivity of SOFIA compared with past and existing facilities. Ground-based observations are possible in the atmospheric windows.

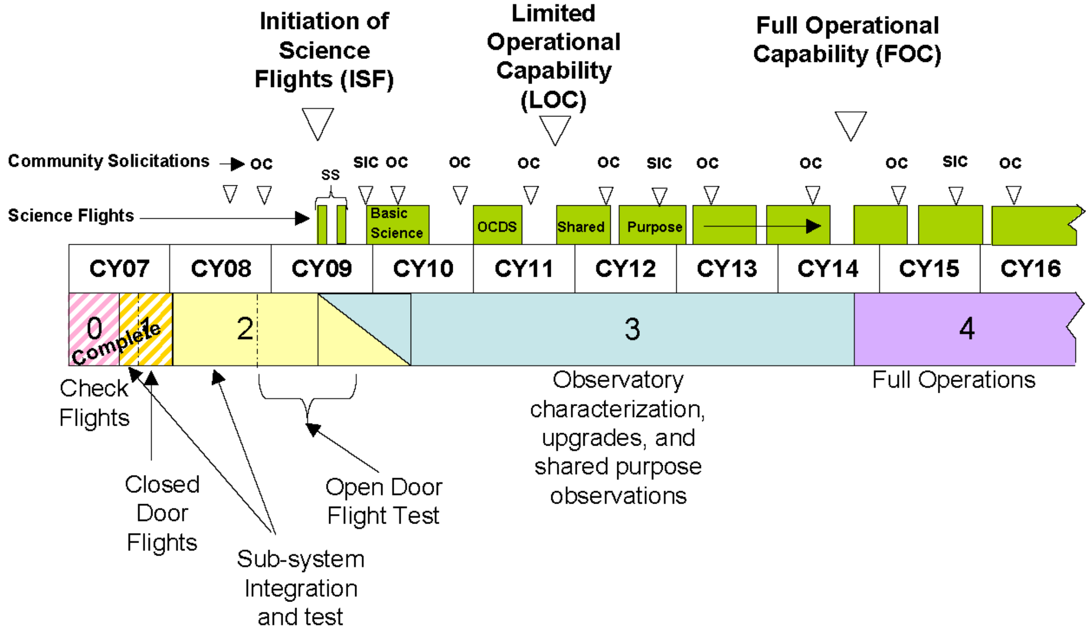

Figure 3. The near term SOFIA development timeline with science activity in green.

SOFIA recently passed a key milestone with the completion of the closed-door flight tests in December 2007.

In early 2008 the aircraft was relocated to Site 9, Palmdale, which will be its ultimate home and the location of the SOFIA Operations Center. The SOFIA Science Center will be located at Ames Research Center.

The development schedule is depicted in Figure 3. It shows that initial science flights are anticipated in 2009, Limited Operational Capability in 2011, and Full Operational Capability in 2014. The initial suite of instruments, (HIPO, FORCAST, GREAT and FLITECAM) includes optical, near and mid infrared cameras, and a heterodyne spectrometer. These four instruments will be ready for Initial Operations. As part of the first series of flights, NASA has invited the community to participate in a series of Short Science observations in the Spring/Summer of 2009 to demonstrate the scientific capabilities of the facility FORCAST and GREAT will be available for these first light observations. Additional capabilities in infrared spectroscopy (FIFI-LS, EXES), far-infrared imaging (HAWK and SAFIRE) and heterodyne spectroscopy (CASIMIR) are expected to be ready for Full Operations. The wavelength coverage and corresponding spectral resolution of the first generation SOFIA instruments is depicted in Figure 4 and are summarized in Appendix B.

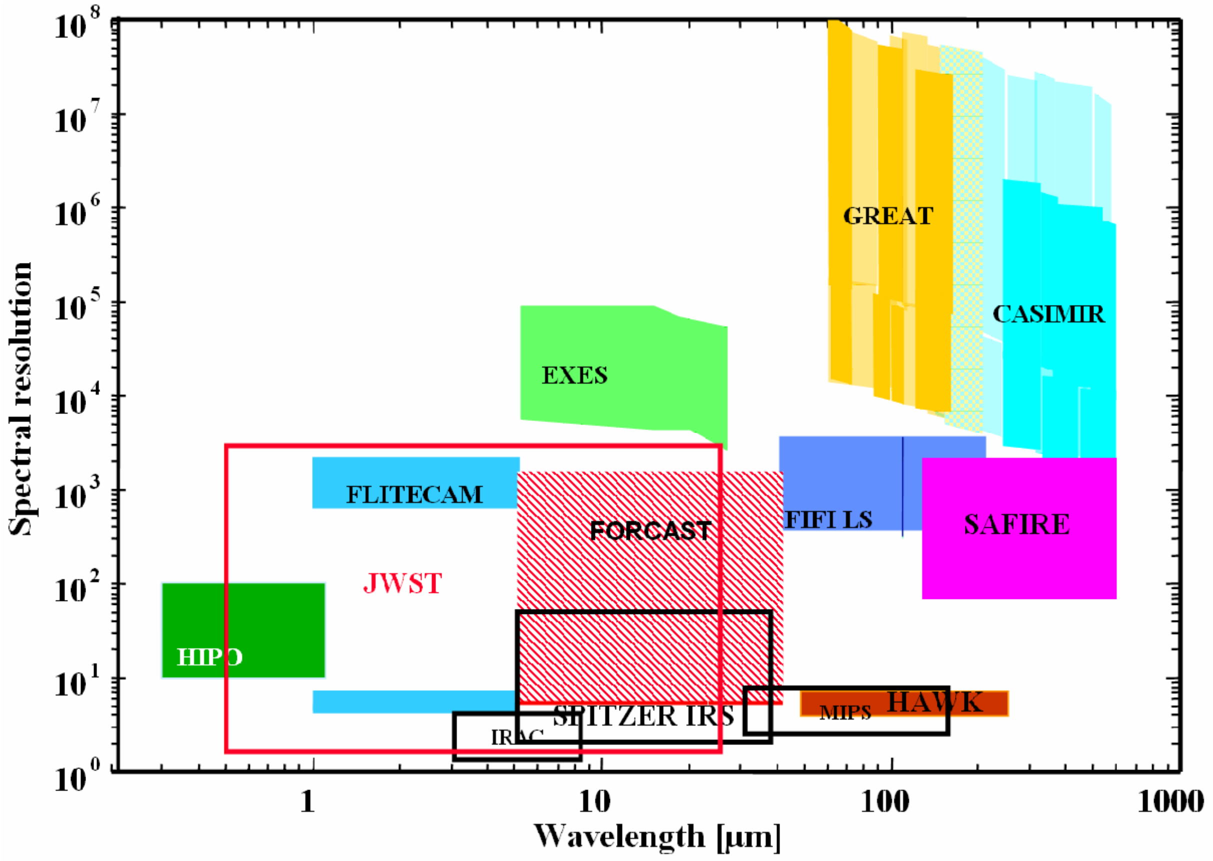

Figure 4 SOFIA First Generation Instruments – Wavelength Coverage vs. Spectral Resolution. Spitzer and JWST capabilities are indicated by the open boxes.

IV. Instrumentation Crystal Ball

a) Detectors

The heart of the new instrumentation capabilities on SOFIA will be advanced detectors. For an airborne facility like SOFIA, the high infrared backgrounds generally mean that the current generation of detectors will have the requisite sensitivity to be background limited. The great advances in astronomical capability will come primarily from increases in detector format.

With the very broad wavelength coverage of SOFIA, a number of detector technologies are required to span this range. At the shortest infrared wavelengths (< 5 µm), large multiplexed photovoltaic arrays of exquisite sensitivity using HgCdTe or InSb are well developed. With nearly ideal photometric characteristics, mosaics of as large as 16 million pixels have been produced and used in astronomy. These detector arrays could form the heart of a new generation of SOFIA imagers and spectrometers.

Similarly, silicon Impurity Band Conduction (IBC) detectors are a well developed technology, offering mega-pixel arrays at wavelengths out to ~30 µm. Much of the astronomical development effort has been driven by low background applications like JWST, however, and significant improvements in well capacity will be needed to make these large format devices useful for ground-based and airborne applications.

At far infrared wavelengths (λ > 30 μm) , the detector systems have undergone spectacular increases in capability. Over the past 40 years, array sizes have grown from single element bolometer systems to arrays as large as 10^4 elements for SCUBA-II. At the same time, sensitivity has increased by over 10^8. As depicted in Figure 5, observation speed, as defined as the product of sensitivity^2 x number of pixels has seen exponential growth, increasing by a factor of two every year for the past four decades! SOFIA will be the only facility that can take full advantage of growth in coming years.

In terms of raw sensitivities, the current generation of infrared detectors can satisfy the SOFIA needs, and the development thrust will be in the production of ever larger arrays at the long wavelengths.

Much of the recent work has focused on large format bolometer arrays. A notable example is the 10^4 pixel array for the SCUBA II instrument on the James Clerk Maxell Telescope. The development of photolithographic techniques for bolometer fabrication, Transition Edge Superconductor detectors, and SQUID readout technology have combined to make such arrays a reality in the far-infrared. Figure 6 shows a single pixel of the SQUID readout. The great advantage of the SQUID technology is that it is well matched to the TES bolometers, both in terms of low noise and sub-Kelvin temperature operation.

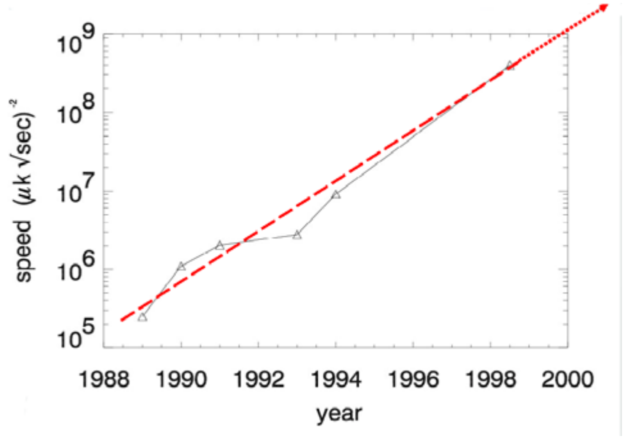

***Figure 5** Plot of observation speed at far infrared wavelengths (Richard's Plot). The speed is proportional to the sensitivity squared x number of pixels. (Moseley 2007)*

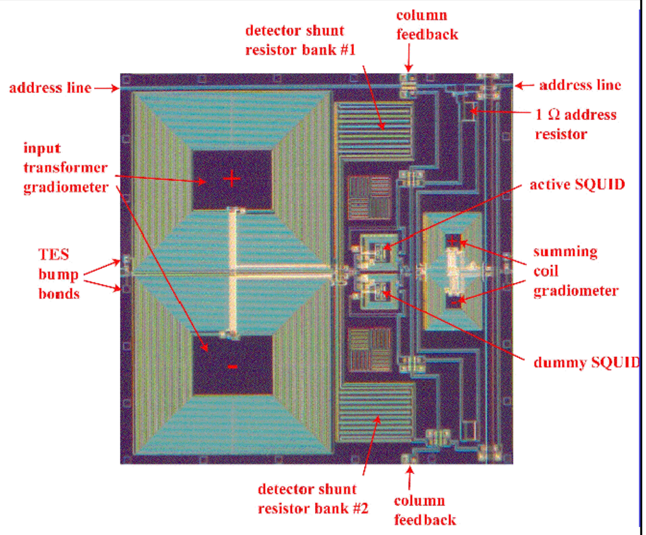

***Figure 6** A SQUID readout circuit developed for the SCUBA II array. This unit cell is replicated for each pixel of the array. (Walton et al. 2004)*

Other kinds of readout technologies are under development for the long wavelengths. One particularly promising technology is the Microwave Kinetic Inductance Detector (MKID). It is a superconducting detector that senses the change in inductance when Cooper pairs are broken by the absorption of radiation. By making the detector part of a resonant circuit, this change in impedance can be sensed. In principle, the MKID detector should allow simple frequency division multiplexing, leading to potentially very large arrays.

The Instrumentation Breakout Session recognized the advances in detector technology as enabling for the next generation of SOFIA instruments. They also recognized that an important distinction between the suppliers of short wavelength detectors on the one hand and the long wavelength direct and heterodyne systems used on SOFIA on the other. The large format shortwave detectors have been procured from aerospace companies, often benefitting from significant military and commercial investments. The longer wavelength systems have typically been developed by university or NASA laboratories. Maintaining this capability is a key concern for the health of the field, and specific SOFIA support will be necessary.

b) Direct Detection Spectrometers

The advancements in detector technology will enable the construction of infrared spectrometers of unprecedented power. Jason Glenn (Colorado) presented the case for a broadband, wide-field, multi-object spectrograph for SOFIA. Both the study of star forming cores and the study of distant galaxies call for a multi-object capability in the 30 – 300 μm range. Such an instrument would have resolutions of 10^3 – 10^4, sufficient to map out the velocity fields in galaxies or star forming regions, and 10^3 independent beams, enough to allow mapping of complicated regions. Glenn emphasized that with recent developments in Transition Edge Superconductor or Microwave Kinetic Induction Devices, basic detector performance should not be a constraint in building such an instrument. Because of the instrumentation advances, this spectrometer would exceed the performance of even space borne instruments on ISO or Herschel. An example of the class of investigation that could be efficiently conducted by such an instrument would be a spectral and spatial line survey of the Galactic Center region. Here, large variations in the line ratios are seen from location to location. A multi-object spectrometer would allow spectral mapping of the full range of Galactic Center

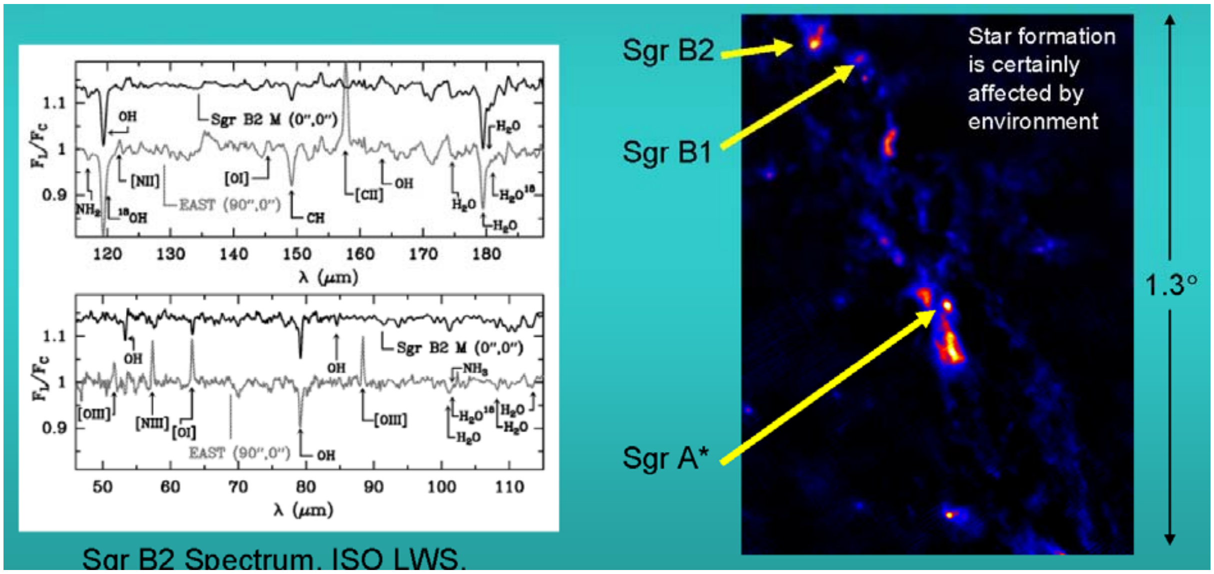

***Figure 7** Observation of two positions near Sgr B2 taken with the ISO LWS spectrometer (Goicoechea et al. 2004), illustrating a variety of environments and the need for extensive mapping. The right pane shows a corresponding 1.1 mm map taken with the Bolocam instrument at the CSO. Figure from Glenn (2007).*

environments. (See Figure 7)

Thomas Nikola (Cornell) presented an alternate concept for a possible future SOFIA spectrometer that also takes advantage of large arrays. The Cornell Mapping Spectrometer (CMS) would combine large bolometer arrays (15K total pixels) with two echelle gratings to produce an integral field spectrometer covering 40 – 220 µm. Figure 8 shows the coverage of just four CMS pointings on M51 superposed on a FIFI observation of the [C II] line taken with the KAO. Each pointing would have 120 beams and 128 spectral elements per beam.

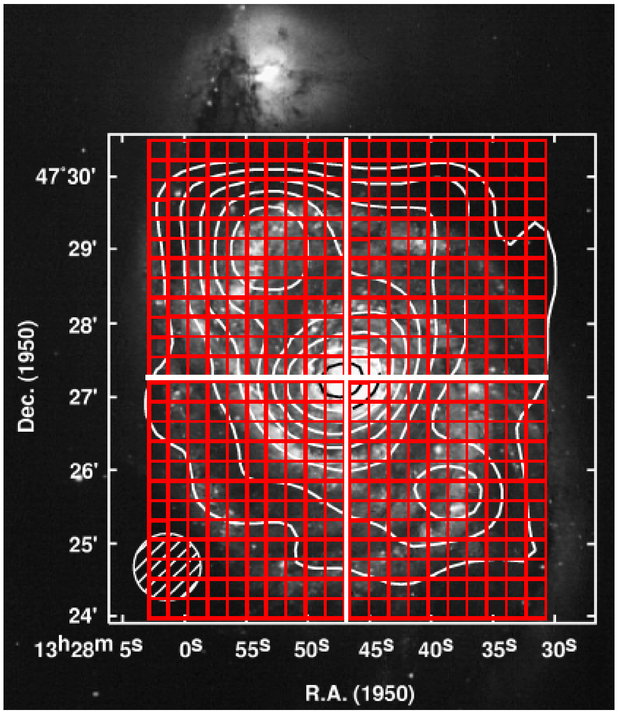

Figure 8 Example observation of M51 with four pointings of the proposed Cornell Mapping Spectrometer. The grid is superposed on [C II] observations taken with FIFI on the KAO. (Nikola 2007)

c) Future Heterodyne Instruments

Significant progress in the development of heterodyne technology was presented at the 2020 Workshop. Much of the work has been spurred by developments for the Herschel observatory. There is now a demonstrated high sensitivity astronomical capability into the THz, enabling the study of some of the most important lines in the interstellar medium. As a facility that can take advantage of new instrumental developments, SOFIA stands to benefit from detector work in the post-Herschel era, particularly beyond the Herschel high frequency limit.

In the 1 to 6 THz regime, Hot Electron Bolometer (HEB) mixers are an area of continuing development. Recent work was presented by J. Gao (SRON Delft), highlighted by a 4.6 THz receiver noise temperature of only 6 times the quantum limit (Figure 9). Despite this large leap in performance, systems at these wavelengths are still far from being limited by fundamental physics. SOFIA is the only facility that can take advantage of new instrumentation developments to explore this poorly observed part of the spectrum.

The largest gains in overall observational capability are likely to come from array technology. In the past 20 years, arrays have become common at infrared wavelengths with revolutionary effects on

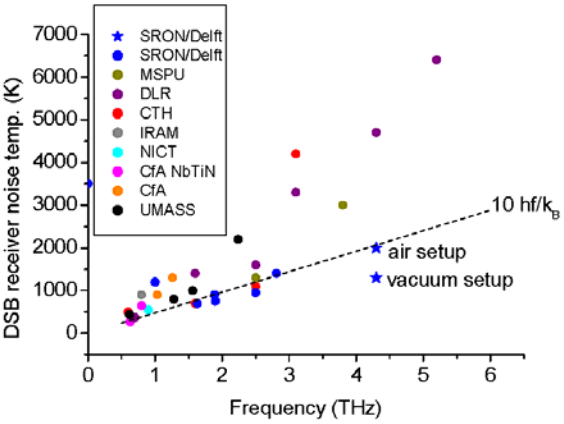

Figure 9. Recent noise temperature measurements for HEB mixers compared to 10X the quantum limit. (Khosropanah et al. 2007)

the field. The technology of multi-pixel arrays is now in its infancy in heterodyne instruments, but progress is rapid. A confluence of developments have made the construction of large THz arrays a possibility. Hot electron bolometer mixer arrays and quantum cascade local oscillator sources are now viable technologies in the sub-millimeter, while micromachining methods can be applied to the fabrication of horn and waveguide components. Perhaps the most daunting aspect of making a heterodyne array has been the back end spectrometer, historically an entire rack of equipment per channel. The development of microcircuit digital spectrometers promises orders of magnitude reductions in size and cost per pixel. Figure 10 shows a section of the SuperCam array being constructed for the Henrich Hertz Telescope for mapping CO at 870 μm. The concept is scalable to the THz wavelengths of SOFIA, and it would provide two orders of magnitude increase in mapping speed over current single channel systems.

d) Polarimetry

Polarimetry represents a potentially important niche for SOFIA as there is no polarimetric capability planned for Herschel, JWST or SPICA. Far infrared polarimetry was one of the most productive areas of research on the KAO, and the expectations should also hold for SOFIA. With the advent of array detectors in the far infrared, significant increases in both speed and precision should be possible.

The first generation SOFIA instruments do not include a polarimeter. To address this deficit, G. Novak (Northwestern University) presented a concept for retrofitting a polarimeter on the HAWC far infrared camera.

In the mid-infrared, spectropolarimetry can be used to advantage in the study of grain properties. The availability of large format arrays enables fast, multibeam instruments that have very low systematic effects.

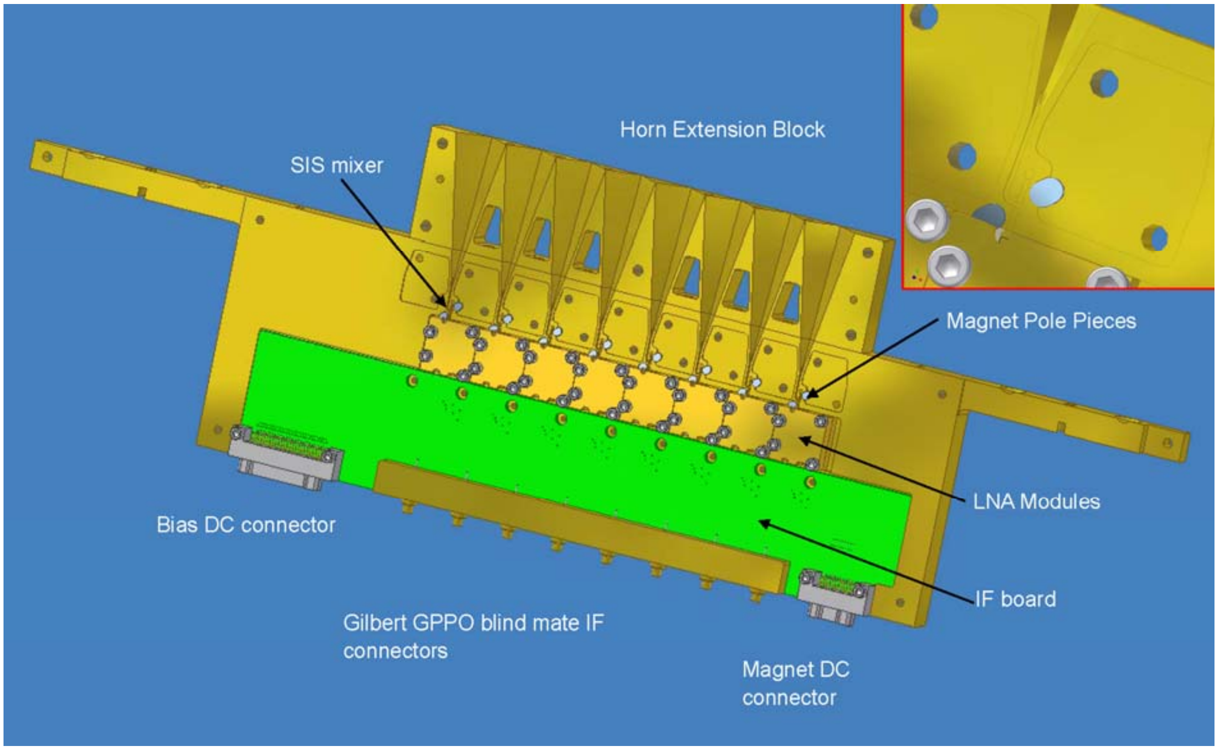

Figure 10 SuperCam heterodyne array front end design. The full array consists of eight of these modules, producing a 64-beam heterodyne array operating at 870 μm. (C. Walker, private communication).

VII. Extragalactic Opportunities

The transformation of the interstellar medium into stars and the subsequent return of the material into the ISM is the fundamental process in the evolution of galaxies. Perhaps the most powerful future SOFIA capability in this area will be a moderate resolution far infrared spectrometer that would enable the mapping in the key cooling lines in galaxies. Such a spectrometer would have resolution matched to the line widths of galaxies (λ/δλ ~ 2000). Table 1 describes some of the important diagnostic tools available to SOFIA. With the anticipated developments in very large detector arrays, a SOFIA spectrometer could have a significant advantage in mapping speeds compared to existing capabilities. For nearby galaxies, SOFIA will have the angular resolution to separate arm/interarm regions in spirals. In particular, the rich legacy of the Spitzer SINGS data set will be complemented by corresponding line maps by SOFIA.

The fine structure lines will also be valuable for the study of more distant galaxies, particularly ULIRGS.

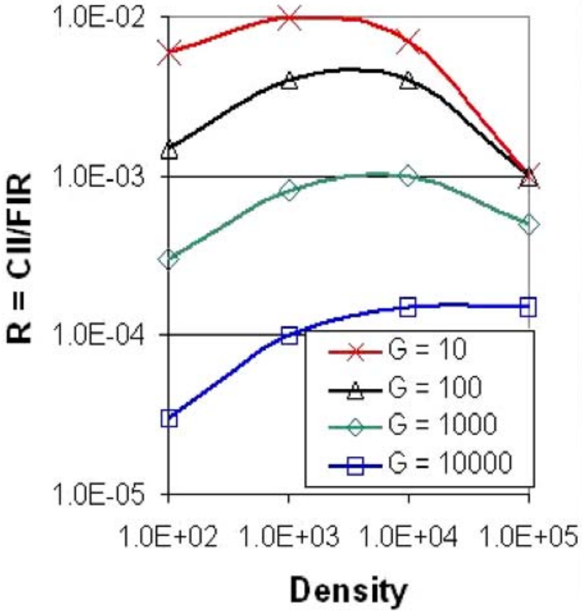

***Figure 11** Ratio of [C II] line intensity to far infrared continuum for different interstellar radiation fields. (Stacey 2007)*

As is the case for the Milky Way, the [C II] line is the brightest line in most star forming galaxies, and can have a luminosity that is 10^{-3} to 10^{-2} of the total far infrared luminosity. The ratio of [C II] to far infrared continuum is a useful measure of the strength of the interstellar radiation field

Table 1 Some Key ISM Diagnostics

Lines	Wavelengths (μm)	Diagnostics
[C II] [O I]	158 63 & 146	PDR Parameters, interstellar radiation field, density and
[N II] [O III]	122 / 205 88 / 52	Line pairs yield gas density
[N II] / [N III]	205 / 57	Hardness of radiation field
[N II]	205	Ionizing Flux
[N II] / [C II]	205 / 158	Fraction of [C II] arising in ionized regions
[N III] / [O III]	57 / 52	Evolution of Abundances

as shown in Figure 11. Large scale mapping by SOFIA would enable the localization of regions of high UV fields associated with young starbursts and AGNs.

In addition to the atomic lines, important information about starburst galaxies can come from a study of mid-J CO lines as demonstrated in the observations of Bradford et al. (2003), Bayet et al. (2004), and Gusten et al. (2006). The observations of NGC 253 indicate that much of the molecular interstellar medium is warm and dense ($T \sim 120$ K, $n \sim 10^4$ cm^{-3}), but the heating cannot be explained by conventional PDR or XDR models. Higher J observations with SOFIA will be needed to better understand the gas excitation.

Our knowledge of the Galactic Center benefits greatly from the legacy of the Kuiper Airborne Observatory. Many of the fundamental structures such as the Circumnuclear Disk (CND) were discovered on the KAO. The CND is the reservoir for material accreting into the central parsec and can serve as a local analog of such disks in galactic nuclei everywhere, illuminating models for mass accretion onto super-massive black holes.

SOFIA also can make contributions in continuum observations. While not having the sensitivity of Spitzer, SOFIA provides much better angular resolution in the 30 to 70 μm wavelength range. The far IR is key to the study of starburst galaxies since this is where the warm dust peaks in emission.

For extragalactic science, the breakout session identified the need for local spectral templates in order to help interpret more distant systems. The wide wavelength coverage of SOFIA will make it a particularly valuable facility. The characterization of dust in various environments is likely to remain an important theme in the coming decades.

The key instrumental needs centered on far infrared spectroscopy. Two classes of instruments are on the extragalactic list of desired instruments. First, a moderate resolution spectrometer ($R \sim 10^3$) for wavelengths beyond 20 μm was the most important need. With anticipated progress in making very large detector arrays, such an instrument could have a powerful long slit or multi-object mode. A second class of highly desired instrument would be desired would be an integral field spectrometer, allowing spectral decomposition of complicated regions.

VIII. Interstellar Medium

The interstellar medium (ISM) is both the source material and the fossil record of star formation in galaxies. A recurring theme at the 2020 Workshop was the importance of the cooling lines in the SOFIA wavelength range. Emission from gaseous species reveal the physical and chemical conditions, are the sole tracers of dynamics, and are the primary coolants of the ISM. As an example of the richness of the far-infrared and sub-millimeter spectra that could be observed with SOFIA, Figure 12 depicts model line spectra from a hot core, a quiescent cloud, and a shock region .

The most important of the interstellar cooling lines is [C II] at 158 μm. It is the dominant emission line of the interstellar medium, and it plays a key role in the transformation of neutral atomic gas into molecular clouds. Unlike the well-observed 21 cm line of atomic hydrogen, [C II] preferentially selects clouds rather than the more diffuse Warm Neutral Medium. SOFIA will be capable of providing both the spatial and velocity resolution to study the detailed structure of atomic clouds as they transition into the molecular state. Although Herschel will be able to observe the [C II] line with the HIFI instrument, SOFIA holds the promise of efficient mapping of cloud

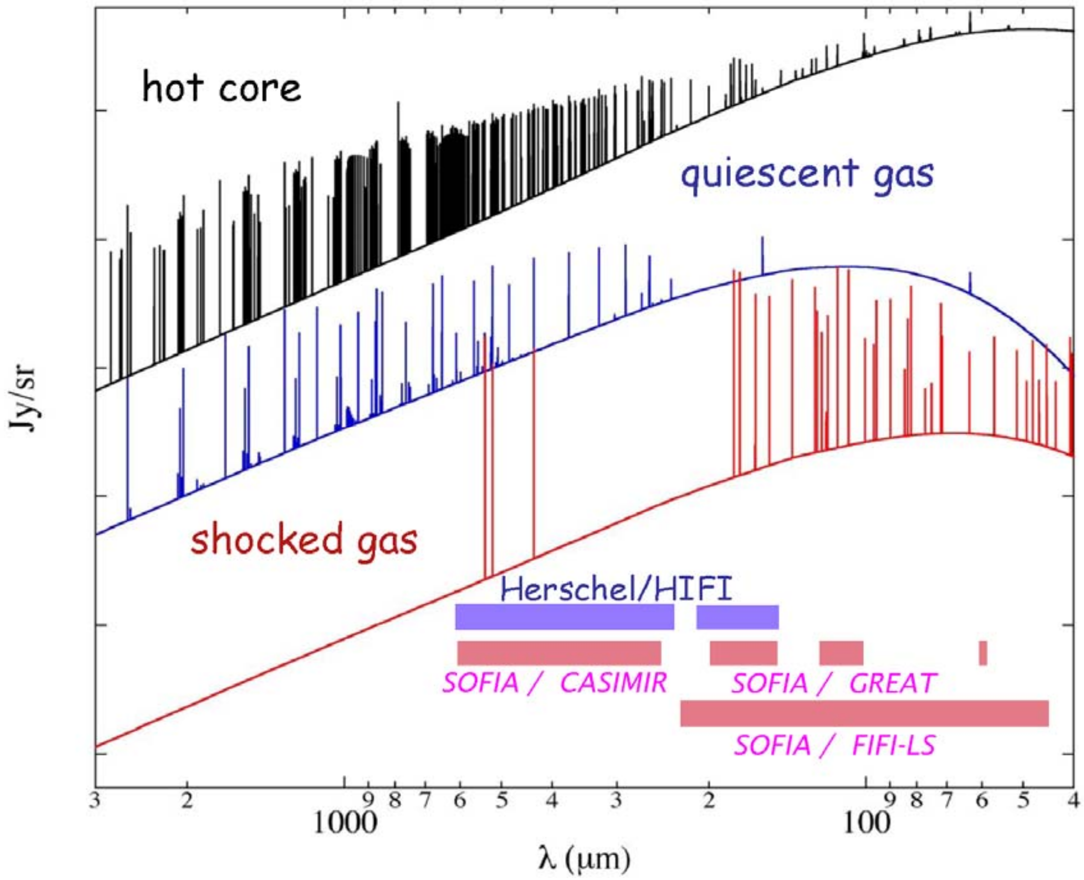

Figure 12 Characteristic spectra from a hot core, quiescent gas, and shocked gas in the interstellar medium, showing the richness of the long wavelength spectra available to SOFIA. Wavelength ranges of key instruments on SOFIA and Herschel are indicated. (Bergin 2007)

complexes with the development multi-pixel heterodyne arrays. A repeated theme is the need for sampling full clouds to understand the formation of structure in molecular clouds. Heterodyne observations of cloud complexes in the [C I], [C II], [N II], and [O I] lines will provide the essential kinematic information in the cloud formation process. (See Figure 13).

One of the mysteries to emerge from ISO spectroscopy is the location of the oxygen in dense clouds. Observations of the [O I] fine structure line at 63 µm suggest that most of the oxygen is in atomic form (Lis et al, 2001; Vastel et al. 2002) . This conclusion, however, contradicts the observed wide scale presence of water in denser regions. With the advanced heterodyne spectrometers that will be available with SOFIA/GREAT and subsequent instruments, the velocity structure in this key line can be explored in enough detail to address this question. In addition, observations of the 145 µm transition of [O I] will help constrain the optical depth and excitation.

The advance of heterodyne technology should be particularly valuable for the observations of the ground state rotational transition of HD at 112.07 µm, first detected in the ISM by Wright et al. (1999) with ISO.. As the dominant deuterium molecule by far, HD is not subject to fractionation complications in the determination of the [D]/[H] ratio. This line has also been detected in absorption against W49 using the ISO LWS spectrometer (Caux et al. 2002). If the association with a molecular cloud along the line of sight is correct, the line ratios suggest a large CO depletion.. SOFIA observations that provide kinematic information will permit direct correlations with existing CO data.

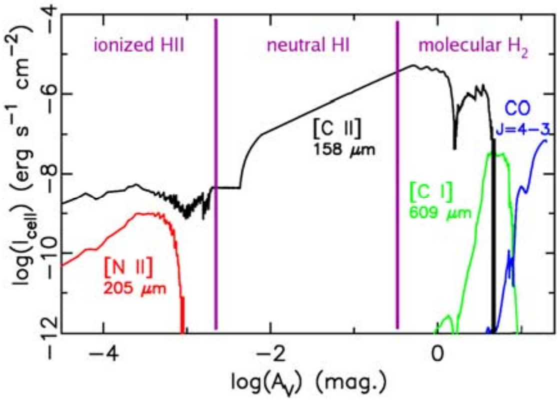

Figure 13 Model of the line intensity from various tracers of the interstellar medium as a function of visual extinction in a PDR. [C II] probes both the ionized and neutral atomic regions, while [N II] is only found ionized regions. (C. Kulesa, private communication).

Dust is the other key component of the ISM. SOFIA will be particularly well suited for studies of the formation of dust and its subsequent processing in shocks. The emission from supernova condensed dust peaks at wavelengths beyond the coverage of JWST but shorter than Herschel. Significant work on the development of dust in supernovae remnants has been done with Spitzer but those studies have been hampered by the limited spatial resolution of Spitzer. Supernova remnants are beautifully complex collections of knot and filaments, and the angular resolution of SOFIA will be needed separate the various environments. SOFIA, for example, will enable the direct comparison of IR emission with individual optical knots to test models of stochastic heating of dust particles by UV photons.

Infrared observations are also useful to quantify the physical characteristics of classical nova outbursts. Abundances in both the dust and the gas can deduced from infrared spectroscopy, and the mobility of SOFIA will be particularly useful in following the time development of these transient phenomena. Among the emission lines that have proven useful in the study of novae are the atomic fine structure lines of [O I] (63 and 145 µm), [O III] (52, 88 µm),

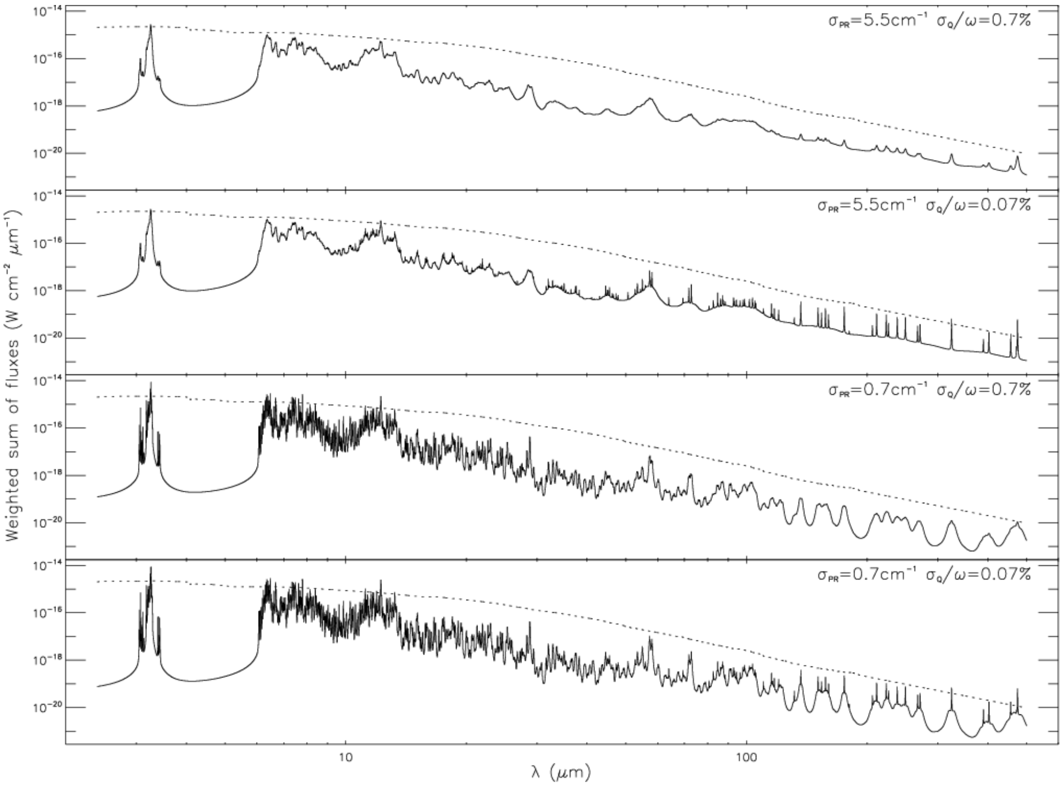

Figure 14 Model spectra for PAH emission from the Red Rectangle for assumptions of rotational excitations and anharmonic widths of the bands. The dust continuum is indicated by the dotted line. (Mulas et al. 2007).

[O IV] (25.9 µm), [C II] (158 µm), [Si II] (34 µm), and [S I] (26 µm) and [S III] (18.7 µm)

Polycyclic Aromatic Hydrocarbons (PAH) have proven to be an important component in the interstellar medium. Carrying a significant fraction of the total carbon, these features promise to be an active area of SOFIA science in the future. The observations of PAH bands in the 15 – 21 µm region by Spitzer (Peeters et al. 2004) has increased interest in larger PAH molecules which are expected to have features in the 10 – 1000 µm wavelength range. Figure 14 from Mulas et al. (2007) shows model far infrared spectra for PAH emission from the Red Rectangle for various molecular parameters. Many of the characteristic bands are best observed in the 100 -200 µm range, which is prime SOFIA territory.

IX. Star and Planet Formation

The starless cores are the birthplaces of stars and represent the initial conditions to star formation., but they are still poorly observed. In the densest cores, most of the heavy elements appear to be frozen out on the surfaces of grains, so the normal tracers such as CO do not give good information about either the density or dynamics of the central regions. In these densest regions, the lines of H_2D^+ and D_2H^+ (1.37 and 1.48 THz, respectively) may be key tracers of the kinematics inside cores and will be observable with SOFIA instrumentation.

The structure of protostellar disks is complex, requiring many different approaches for investigation. SOFIA will offer unique instrumental capabilities including high resolution infrared spectroscopy and spectropolarimetry. For even the nearest star forming regions, the crucial inner disk regions are beyond the reach of direct imaging, but spectroscopy can provide information about composition, temperature structure, and dynamical conditions. Of particular promise is the use of CH_4 as a tracer of forming planets. Two effects may enhance CH_4 abundances in these environments. Homogeneous thermochemistry heavily shifts the CO/CH_4 ratio in favor of methane at the high pressures expected in planet forming regions (Prinn & Fegley 1989). Additionally, it is expected that CH_4 will be formed from CO on grains via Fischer-Tropsch reactions at temperatures above 700K (Boogert et al. 2004), further enhancing the CH_4 abundance.

Water in disks is another key component with great diagnostic capabilities. Because of telluric absorption, observation from the ground are limited to a few high energy lines. EXES or a future high resolution far-infrared spectrometer on SOFIA would be able to explore a much wider range of excitation conditions. Hot (~1000 K) water, which has already been detected by Spitzer probes conditions in the inner disks, while cooler water provides information about disks beyond the snow line (Meijerink et al., in preparation).

SOFIA spectroscopy will be able to investigate the evolution of gas in young disks. The [O I] 63 μm line has been observed in numerous T-Tauri stars with ISO (e.g., Spinoglio et al. 2000; Creech-Eakman et al. 2002). The interpretation of these observations has been complicated by the large beam sizes and poor angular resolution. Small beam observations with resolved line profiles with SOFIA would permit identification of emission from inner disk regions (Meijerink et al. 2008). The evolution of gas in the transition from protostellar to debris disks is also ripe for study. Herschel PACS will be able to detect ~0.01 M_{Earth} of gas in the gas giant zone via observations of the [O I] 63 μm line (Su et al. 2007). With advanced heterodyne systems, on SOFIA these limits could be improved.

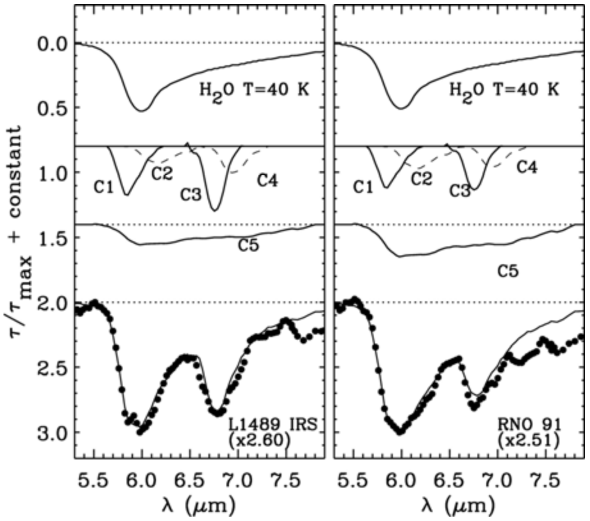

***Figure 15** Examples of ice spectra taken with the Spitzer IRS spectrometer toward two young stellar objects. The decomposition into H_2O ice and other components is demonstrated. (Boogert et al. 2008)*

In the 2020 time period, the NIRSpec and MIRI instruments on JWST will provide spectra of exquisite sensitivity in the important 1 – 28 μm range, where many of the prebiotic molecules have strong transitions. Many of the studies, however, will require significantly higher spectral resolutions, which SOFIA will provide for the brightest objects.

Boogert et al. (2008) have demonstrated the utility of spectra in the 5 – 8 μm wavelength range for the characterization of ices. (See Figure 15). They have found that much of this absorption is due to simple species likely formed on grain surfaces such as CH_3OH, NH_3, HCOOH, H_2CO, and $HCOO^-$. The relative abundances of these carriers holds information on the grain processing history in protoplanetary disks. For example, the fact that the ices have been

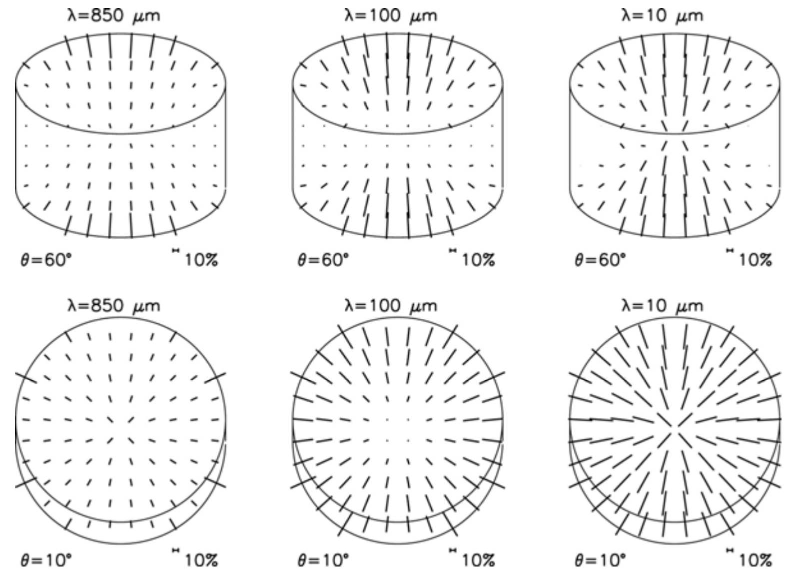

Figure 16 Predicted polarization images for a T-Tauri star over wide range of wavelengths and two inclination angles. (Cho and Lazarian 2007)

observed in both high and low mass young stellar objects reduces the importance of UV processing in the ice chemistry. SOFIA will provide an important platform for continuation of these studies for various lines of sight, particularly after the helium runs out on Spitzer.

In the far-infrared, the 45 μm libration band of crystalline water ice should be an important diagnostic to probe ice content and thermal history of disks. SOFIA FIFI-LS will provide a unique capability to observe this feature until SPICA flies.

One of the outstanding issues in star formation is the exact role of magnetic fields. The fields appear to play a role in supporting some clouds from collapse, but the relative importance of magnetic fields in determining fundamental properties like the timescale of collapse or the initial mass function is the still the subject of much debate. Far infrared polarimetry is one method of directly assessing the importance of magnetic fields in molecular clouds. At long wavelengths, the scattering efficiency is very low, and the polarized flux is due to dichroic emission from aligned grains. Li et al (2006) presented recent observations of the NGC 6334 GMC with the SPARO polarimeter. This instrument, located at the Amundsen-Scott South Pole station Viper telescope produced polarization maps at 450 μm. By comparing the field disorder seen in their maps with predictions from MHD simulations, they find that the energy density in magnetic fields is comparable to turbulent energy.

Protostar/disk systems also have polarimetric signatures that will allow researchers to address questions about disk geometry, the role of magnetic fields, and grain composition. For example, Cho and Lazarin (2007) have presented models of the polarized flux from magnetic T-Tauri stars. Because the signal from a disk comprises of both a scattered and emitted components, observations at a wide range of wavelengths will be required to disentangle the various emission regions. Figure 16 shows predicted polarization images for a range of wavelengths. For unresolved sources, polarizations of up to 10% are predicted.

Spectropolarimetry will be a SOFIA-unique capability for the study of solid state components in disks. An example of this kind of investigation is the recent work of Chiar et al (2006) who compared the polarization characteristics of the 3.4 μm hydrocarbon feature compared to the well-observed 9.7 μm band. The short wavelength band is unpolarized while the 9.7 μm silicate band is polarized toward the Galactic Center. The implication is that the hydrocarbons in the diffuse interstellar medium form a separate population from the silicate grains, challenging standard core-mantle grain models.

SOFIA will be able to add valuable observations in the study of extrasolar planets. In particular, observations of planet transits at a variety of wavelengths has been shown to be a powerful technique for deducing the composition and structure of extra solar planet atmospheres (Fortney & Marley 2007; Barman 2007; 2008). With low expected scintillation noise, SOFIA should produce transit data very high quality, and the wide wavelength coverage will be valuable in composition studies. Initially, the SOFIA program will focus on the two or three brightest known transiting planets. The many on-going programs to find extra solar planets are expected to add numerous observation candidates to this list over SOFIA's lifetime (Dunham et al. 2005).

X. Solar System

The Trans-Neptunian Solar System should be a rich area of study for SOFIA with more than 1500 Kuiper Belt Objects known. As some of the most primitive objects in the Solar System, the KBOs provide a glimpse into the early conditions of planet formation. SOFIA has an important niche in providing a spectroscopic capability in the L and M bands, shorter than the range provided by Spitzer IRS. In this wavelength range absorptions by H_2O ice, CH_4 ice, and N_2 are strong. Figure 17 shows a spectrum of 90377 Sedna in the near infrared (Emery et al. 2007). While the Spitzer photometric observations are best fit using a combination of both CH_4 and H_2O, 3 – 5 μm spectra are clearly needed for a clear identification.

Comets represent some of the least processed materials in Solar System, and their study has provided important insights to the era of giant planet formation. Both the volatile and non-volatile components in comets can be studied with SOFIA spectroscopy, and the composition and processing history of the minerals can be revealed by analyzing the detailed shapes of the spectral features in the infrared bands. For example, Spitzer and ISO spectra of comets have been modeled with combinations of PAHs, carbonates, and phyllosilicates, as shown in Figure 18, although the evidence for PAHs and hydrated silicates is a matter of debate. The key diagnostics are in the SOFIA wavelength range, and they can be observed at moderate resolution.

The most important volatile in comets is water, and the ability of SOFIA to fly above the bulk of the terrestrial water makes its uniquely poised to observe them. Water production rates, coma temperature, and nuclear spin temperature derived from ortho-to-para ratios provide constraints on solar nebula models since this ratio retains a memory of the conditions when H_2O was last equilibrated.

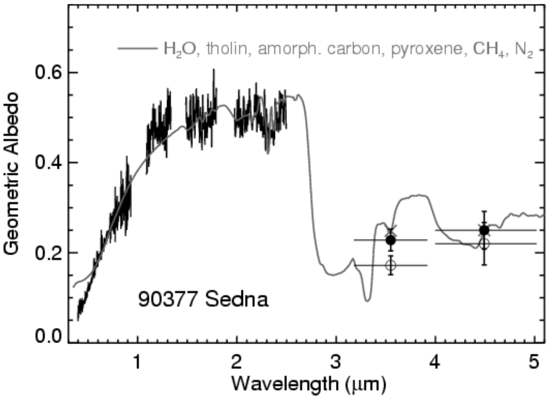

***Figure 17** Ground-based spectra of 90377 Sedna with IRAC photometric points at 3.6 and 4.5 μm. The solid line is a model spectrum. To fit the data, both CH_4 and H_2O ices are required. (Emery et al. 2007).*

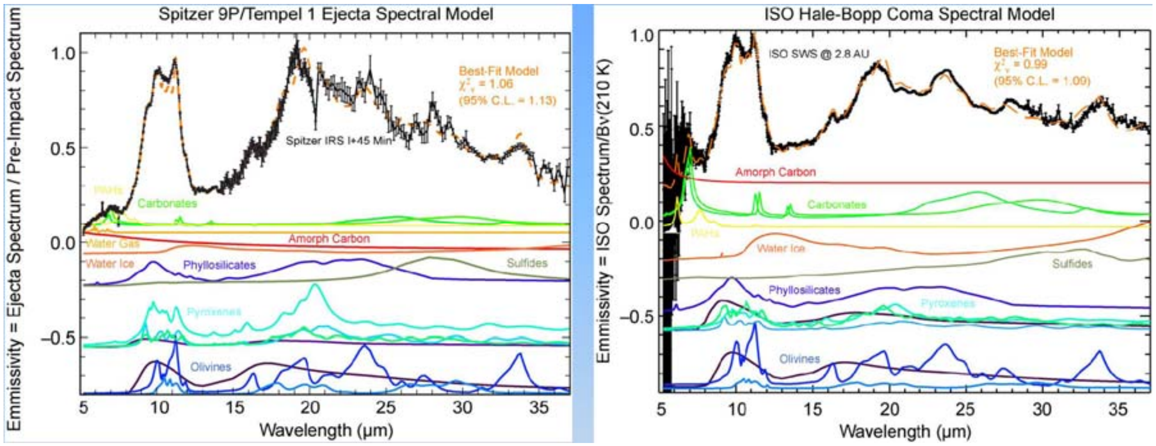

Figure 18 Spitzer and ISO spectra of comets along with model fits using PAHs, carbonates, and phyllosilicates. (Adapted from Lisse 2007 and Lisse 2006; Woodward 2007)

The Solar System and Exoplanets breakout session identified a number of key niches for the facility. Most importantly, the 28 – 160 μm wavelength range will prime SOFIA territory. For much of the anticipated 20-year operational lifetime, SOFIA will be the only facility available. In particular, the potential to provide high resolution spectroscopy will be a key capability.

The ability of SOFIA to campaign from anywhere on earth is a major strength when dealing with transitory phenomena like comets. Additionally, the observation of comets at small solar elongation angles will be enhanced by the facility's low elevation limit.

The mobility of SOFIA also enhances the opportunities for observing occultations of stars by planets and smaller solar system objects, particularly considering much of the Earth's surface is covered by water. Elliot and Kern (2003) have estimated that SOFIA will have access to ~200 observable KBO occultations per year, whereas even an optimized portable system would only get 4 events annually. Such observations should address questions about atmospheric structure and composition as well as temporal variations in rings.

The breakout session also identified occultations by extra solar planets as a potentially exciting area of future SOFIA science. Surveys such as Kepler will provide numerous candidates for follow up study. As has been demonstrated by the exciting observations from Spitzer, spectrally resolved occultations have the possibility of revealing atmospheric composition of extra solar planets. A number of technical questions will need to be addressed. Most importantly, the role of scintillation noise on SOFIA will need to be evaluated.

XI. Summary

Of necessity, the vision of SOFIA instrumentation and science gets blurrier the farther out in time one considers. The participants at the Workshop were, however, able to identify a number of clear directions where significant advancements in measurement capabilities will be possible. In particular, the continuing drive to larger and larger detector arrays (both direct detection and heterodyne) will enable instruments of great power. To maintain the vitality of the vision, continued support for the development of new instrumentation will be needed.

For SOFIA, high resolution infrared and far-infrared spectroscopy will be, for the foreseeable future, a unique niche. At the highest resolutions, the advantage of a cold telescope are reduced, while physics forces the size of spectrometers to be large. Hence, the advantages of a space-borne observatory are minimized. Ground based facilities will continue to develop, but for much of the wavelength range of interest, the atmosphere is simply opaque.

Until the era of SPICA and SAFIR, SOFIA will be the only operating astronomical facility between 30 and 300 µm. (Figure 19).

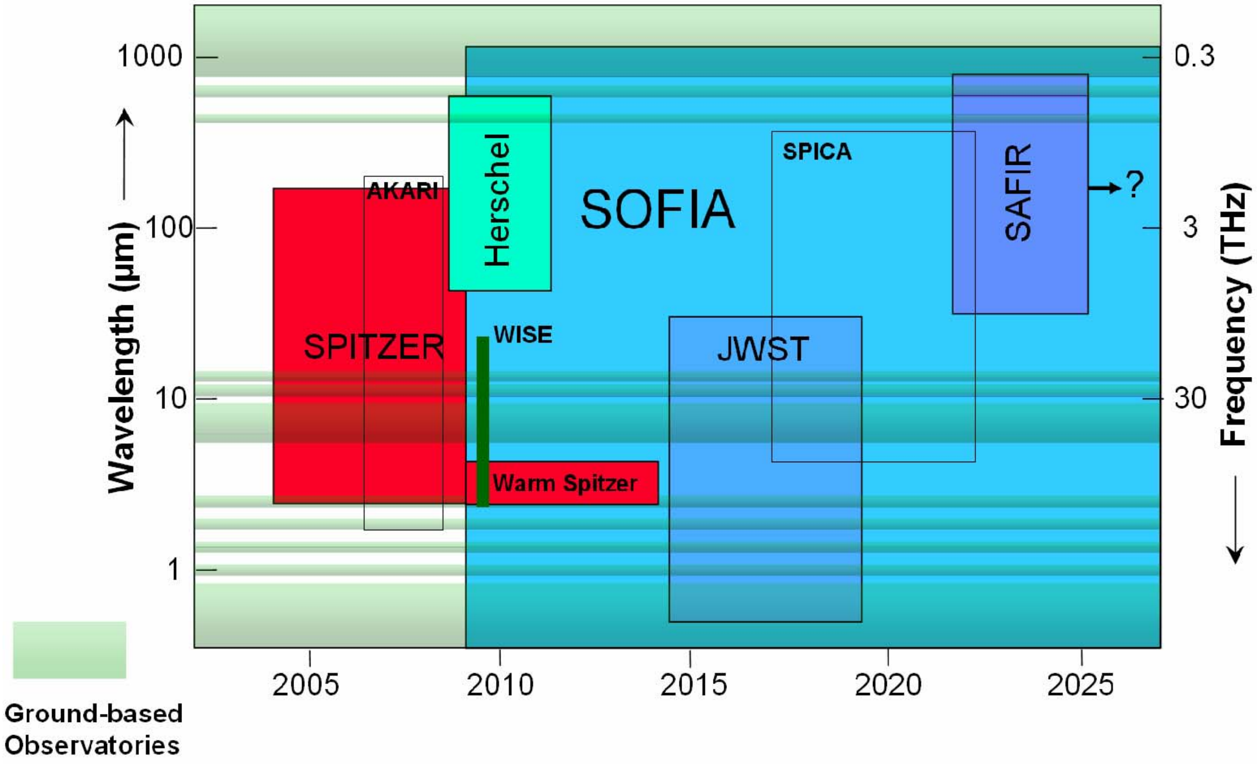

Figure 19. The context of SOFIA with other major infrared facilities in the next decade. (Becklin 2007).

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Appendix A. SOFIA 2020 Workshop Organization

Scientific Organizing Committee

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Tom Phillips Caltech
Jonas Zmuidzinas Caltech

Appendix B SOFIA First Generation Instruments

The SOFIA First Generation instruments are summarized in the following table. The Facility Instruments are FORCAST, FLITECAM, and HAWC, while the other instruments are Principal Investigator instruments. The availability date in the table is the anticipated delivery date of the instrument to the facility. Much more information about the suite of SOFIA instruments can be found at the SOFIA website:

http://www.sofia.usra.edu/Science/instruments/sci_instruments.html

Name	**Description**	**Institution**	**Wavelengths** **Spectral Resolution**	**Availability**
FORCAST	Mid IR Camera and GRISM Spectrometer.	Cornell	$\lambda = 5 – 40\ \mu m$ R ~ 200	2009
GREAT	Heterodyne Spectrometer	MPIfR, KOSMA, DLR-WS	$\lambda = 60 – 200\ \mu m$ $R = 10^6\ 10^8$	2009
FIFI-LS	Imaging Grating Spectrometer	MPE	$\lambda = 42 – 210\ \mu m$ R = 1500 - 3000	2009
FLITECAM	Near Infrared Camera	UCLA	$\lambda = 1 – 5\ \mu m$ R up to ~1300	2010
HIPO	High Speed Photometer for Occultations	Lowell Obs.	$\lambda = 0.3 – 1.1\ \mu m$	2010
HAWC	Far Infrared Bolometer Camera	U. Chicago	$\lambda = 50 – 240\ \mu m$	2011
CASIMIR	Heterodyne Spectrometer	Caltech	$\lambda = 200 – 600\ \mu m$ $R = 3 \times 10^4 – 4 \times 10^5$	2011
EXES	Echelon Spectrometer	U. Texas	$\lambda = 5 – 28\ \mu m$ $R = 3000, 10^4$, or 10^5	2011
SAFIRE	Imaging Fabry-Perot Bolometer Array Spectrometer	GSFC	$\lambda = 145 – 655\ \mu m$ R = 1000 - 1800	2012