The Stratospheric Observatory for Infrared Astronomy (SOFIA)

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ABSTRACT

The joint U.S. and German Stratospheric Observatory for Infrared Astronomy (SOFIA) Project will operate a 2.5-meter infrared airborne telescope in a Boeing 747SP. Flying in the stratosphere at altitudes as high as 45,000 feet (13.72 km), SOFIA enables observations in the infrared and submillimeter region with an average transmission of ≥80%. SOFIA has a wide instrument complement including broadband imaging cameras, moderate resolution spectrographs capable of resolving broad features due to dust and large molecules, and high resolution spectrometers suitable for kinematic studies of molecular and atomic gas lines at km/s resolution. The first generation and future instruments will enable SOFIA to make unique contributions to a broad array of science topics. SOFIA began its post-modification test flight series on April 26, 2007 in Waco, Texas and will conclude in winter of 2008-09. SOFIA will be staged out of Dryden's aircraft operations facility at Palmdale, Site 9, CA for science operations. The SOFIA Science Center will be at NASA Ames Research Center, Moffet Field, CA. First science flights will begin in 2009, the next instrument call and first General Observer science call will be in 2010, and a full operations schedule of ~120 flights per year will be reached by 2014. The observatory is expected to operate for more than 20 years. The sensitivity, characteristics, science instrument complement, future instrument opportunities, and examples of first light and early mission science are discussed.

Keywords: Infrared astronomy, submillimeter astronomy, airborne astronomy, SOFIA, NASA

1. INTRODUCTION

NASA's new Stratospheric Observatory For Infrared (IR) Astronomy (SOFIA), the Spitzer Space Telescope[1, 2], Herschel Space Observatory[3], and James Webb Space Telescope (JWST)[4] will be the premier observatories for IR and

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

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Submillimeter astronomy operated by the Unites States and Europe during the period from 2009 until well beyond 2030. SOFIA (Figure 1), a joint project of NASA and the German Space Agency (DLR), is a 2.5-meter telescope in a Boeing 747-SP aircraft designed to make sensitive IR measurements of a wide range of astronomical objects.

1.1 SOFIA's Operational Altitude and Flight Range

SOFIA will fly at altitudes as high as 45,000 feet (13.72 km), above 99.8% of the obscuring atmospheric H_2O vapor, and will collect radiation at wavelengths from 0.3 µm to 1.6 mm with ≥ 80% transmission (see Figure 2). At this altitude the typical precipitable water column depth is less than 10 µm. From the transmission data shown in Figure 2, it is evident that, except for a few very narrow bands in the mid-IR that are completely blocked by telluric CO_2 and O_2, the IR and submillimeter window opens up substantially at aircraft altitudes.

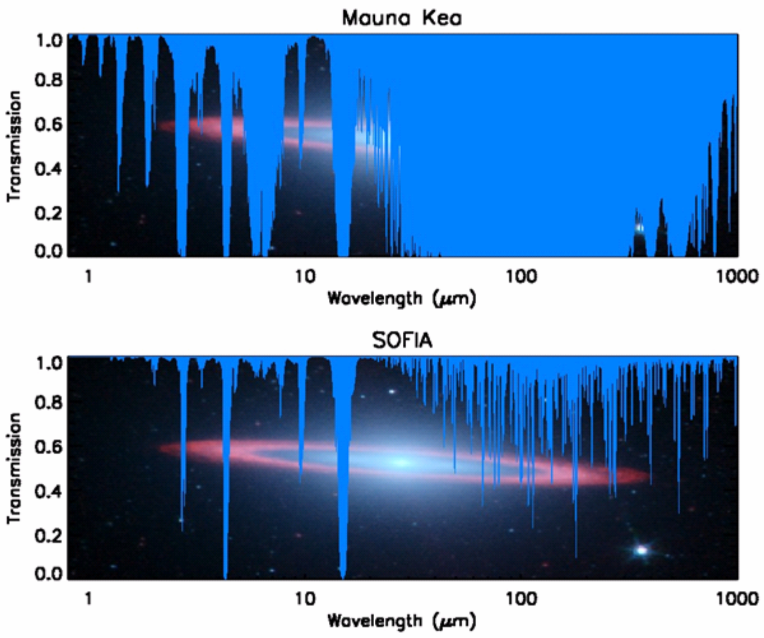

Fig. 2. The typical atmospheric transmission at an altitude of 45,000 feet as compared to the transmission on a good night at Mauna Kea (13,800 ft. msl). From 1 to 1000 µm, the average transmission is ≥ 80% except in the center of absorption lines due to mostly telluric H_2O, CO_2, and O_2. Background image: IRAC false color image of the Sombrero Galaxy, courtesy of NASA/JPL-Caltech.

The Dryden Aircraft Operations Facility in Palmdale, CA is the home port of *Clipper Lindbergh*, the SOFIA aircraft, but the plane will occasionally operate from other bases world-wide, including bases in the southern hemisphere. The mobility of SOFIA will enable observations at any declination in the sky and will facilitate timely observations of transient events such as variable stars, comet apparitions, occultations, and nova and supernova explosions. SOFIA is poised to provide community-wide opportunities for forefront science, invaluable hands-on experience for young researchers, and an extensive and unique education and public outreach program. With observing flexibility and the ability to deploy new and updated instruments, the observatory will make important contributions towards understanding a variety of astrophysical problems well into the 21st century.

1.2 Program Status and Overview

The finished Nasmyth telescope, supplied by DLR, has been mated into the modified aircraft and was tested in 2004. All major structural modifications to the aircraft were completed in early 2006 at L-3 Communications Integrated Systems in Waco, Texas. First test flights of the observatory began in April 2007 after which it was ferried to Dryden Flight Research Center, CA where further flight testing and development has been conducted. Closed door testing was completed in January, 2008. Delivery of the door motor and coating of the primary mirror will occur during the summer of 2008. The first open door flights will begin at Dryden's Palmdale, CA site in early 2009. SOFIA will see first light in 2009, and is planned to make more than 120 8-10 hour scientific flights per year for at least 20 years.

2. SCIENCE OPERATIONS AND SCHEDULE

The SOFIA Science and Mission Operations Center (SSMOC) is located at NASA Ames Research Center in Moffett Field, 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 investigation teams per year, selected by a peer reviewed proposal process. An on-going instrumentation development program will ensure that the facility is operating at the state-of-the-art during its flight lifetime. The first call for Next Generation Instruments will occur in 2010.

2.1 General Observer Opportunities

Early Science with FORCAST and GREAT will occur in 2009. These flights, limited in scope, will call for collaboration with the Principle Investigators (PIs) of FORCAST and GREAT. Routine observations will begin in 2010. A first call to the astronomical community for early science short-duration proposals will occur in late summer of 2008, and a call for more extensive early science opportunities will be released in December 2008. The first call for General Observer (GO) science proposals will occur in 2009. There will be future GO science calls every 12 months. The first GO flight will occur in 2010, with ~ 20 GO science flights annually on a shared risk with the SI PIs until full science operations begin in 2014. There will be additional GO flight opportunities with Facility Instruments.

2.2 Calls for New Instrumentation Developments

SOFIA will provide the astronomical community with unique opportunities to conduct cutting-edge scientific research and with opportunities for invaluable hands-on experience with instrumentation development for young researchers. The SOFIA Project will offer an extensive education and public outreach program. With observing flexibility and the ability to deploy new and updated instruments, the observatory will make important contributions towards understanding a variety of astrophysical problems well into the 21st century. The next call for instruments will be at first science in ~FY2010. There will be additional calls for new instrumentation development every 3 years and the Project anticipates that there will be one new instrument or upgrade per year. The approximate funding level for the new science instrument development program will be ~$10 M/yr.

3. SOFIA FIRST GENERATION INSTRUMENTS

Nine first generation Science Instruments (SIs) have been selected and are under development (Table 1). The selection includes three Facility Class Science Instruments (FSIs): HAWC, FORCAST, and FLITECAM. The FSIs will be maintained and operated by the science staff of the SSMOC for the general science community. In addition, there are six

Table 1. SOFIA First Light Instrument Summary

SOFIA Instrument	Description	Built by	λ range (μm) spectral res ($\lambda_0/\Delta\lambda$)	Pre-ship Review
FORCAST	Faint Object InfraRed CAmera for the SOFIA Telescope Facility Instrument - Mid IR Camera and Grism Spectrometer	Cornell	5 - 40 R ~ 200	Feb, 2009
GREAT	German Receiver for Astronomy at Terahertz Frequencies PI Instrument - Heterodyne Spectrometer	MPIfR, KOSMA DLR-WS	60 - 200 R = 10^6 - 10^8	Mar, 2009
FIFI LS	Field Imaging Far-Infrared Line Spectrometer PI Instrument w/ facility-like capabilities - Imaging Grating Spectrometer	MPE, Garching	42 - 210 R = 1500 - 3000	Oct, 2009
FLITECAM	First Light Infrared Test Experiment CAMera Facility Instrument - Near IR Test Camera and Grism Spectrometer	UCLA	1 - 5 R~1300	Feb, 2010
HIPO	High-speed Imaging Photometer for Occultation Special PI Instrument	Lowell Obs.	.3 - 1.1	Mar, 2010
HAWC	High-resolution Airborne Wideband Camera Facility Instrument - Far Infrared Bolometer Camera	Univ of Chicago	50 - 240	Mar, 2011
CASIMIR	CAltech Submillimeter Interstellar Medium Investigations Receiver PI Instrument - Heterodyne Spectrometer	Caltech	200 - 600 R = $3x10^4$ - $4x10^5$	Sep, 2011
EXES	Echelon-Cross-Echelle Spectrograph PI Instrument - Echelon Spectrometer	Univ of Texas	5 - 28 R = 10^5, 10^4, or 3000	Sep, 2011
SAFIRE	Submillimeter And Far InfraRed Experiment PI Instrument - Imaging Fabry-Perot Bolometer array spectrometer	GSFC	145 - 655 R = 1000 - 1800	May, 2012

PI Class SIs that will be maintained and operated by the PI teams at their home institutions. General investigators will be able to propose for these instruments in collaboration with the PI team. Two of the PI Class instruments are being developed in Germany. Facility instruments are maintained and operated by the SOFIA science staff for the general science community. Their pipeline-reduced data will be archived.

A great strength of an airborne observatory is that SIs can be repaired in flight if necessary and exchanged regularly to accommodate changing science requirements and new technologies. Furthermore, much larger, more massive, and more complex instruments can be flown on the SOFIA aircraft than can be flown on most spacecraft payloads. Likewise, heat dissipation and power consumption are of lesser concern than for satellite missions. SOFIA will take full advantage of these characteristics. The first generation of nine instruments is very diverse. Figure 3 illustrates the spectral discovery space of SOFIA's nine first generation instruments, that cover the visible, the near, mid- and far-IR, and submillimeter wavelength regions. In spectral resolution terms, the instruments include imaging cameras with narrow photometric band, moderate resolution spectrometers geared towards studies of broad dust and molecular features, and high-resolution spectrometers capable of velocity-resolved gas phase line studies.

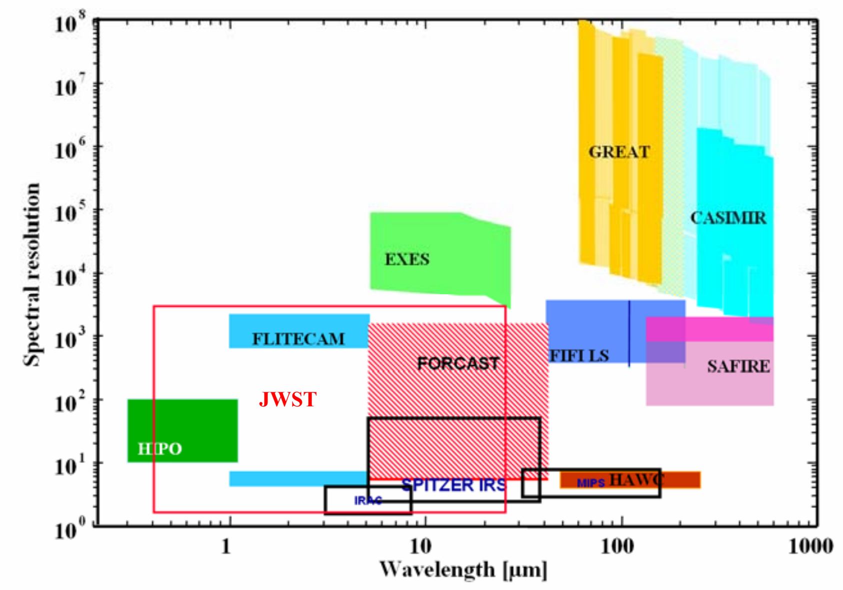

Fig. 3. SOFIA first generation instruments shown in a plot of log spectral resolution vs. log wavelength. Black boxes are Spitzer Space Telescope Science Instruments (IRAC, IRS, and MIPS) for comparison. JWST (red box) will cover the 0.3 to 27 µm spectral region at resolutions as high as 3000. FORECAST and GREAT are the first-light instruments.

The advantage of an airborne observatory over space-based missions to rapidly incorporate instrument improvements and other instrument upgrades in response to new technological developments will be a cornerstone of the SOFIA mission. Technology is still expanding rapidly in the far-IR and major advances in sensitivity and array size are expected. New technologies expected to occur during SOFIA's lifetime were recently explored at a workshop entitled "SOFIAS's 2020 Vision: Scientific and Technological Opportunities," held at Caltech during December 6-8, 2007 in Pasadena, CA.[5] SOFIA will support a technology development and new instrumentation program that will provide a new instrument complement and thus a new mission every ~10 years at the cost of the $10 million per year instrument development program alone.

4. SOFIA'S CAPABILITIES AND COMPARISON WITH OTHER OBSERVATORIES

SOFIA will observe at wavelengths from 0.3 µm to 1.6 mm and will be capable of high resolution spectroscopy ($R \geq 10^4$) at wavelengths between 5 and 150 µm. Its 8 arcminute diameter field of view (FOV) will allow the use of very large format detector arrays. Despite the fact that an airborne mission generally has much higher IR background radiation than a space-based mission, the 2.5-meter 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 IRAS space mission (see Figure 4). SOFIA will match or be more sensitive than the ISO space mission at high spectral resolution. With its capability for diffraction-limited imaging beyond 25 µm, SOFIA will give us the sharpest view of the sky provided by any current or developmental IR telescope operating in the 30 to 60 µm region. In addition, no space-based mission is presently envisioned with a spectral resolution exceeding 3,000 in the 3 to 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. Particular advantages of SOFIA over space-based observatories include:

- Ready observer access to the telescope allowing instruments to be repaired in flight and changed between flights

- A low-risk ability to incorporate new science-enabling instrument technologies and to create a whole "new" observatory at a reasonable cost several times during the lifetime of the facility

- Opportunity for continuous training of instrumentalists to develop and test the next generation of instruments for both sub-orbital and space applications

- Mobility, which allows access to the entire sky without visibility restrictions for timely follow-up of transient events and a vastly increased number of stellar occultation events

- Unique opportunities for educators and journalists to participate first-hand in exciting astronomical observations

SOFIA science will complement and exploit the availability of data from other existing facilities such as Spitzer, SMA, and ASTRO-F and future facilities such as WISE, Herschel, ALMA, and JWST. Herschel and SOFIA will now start science operations at approximately the same time, in mid-2009.

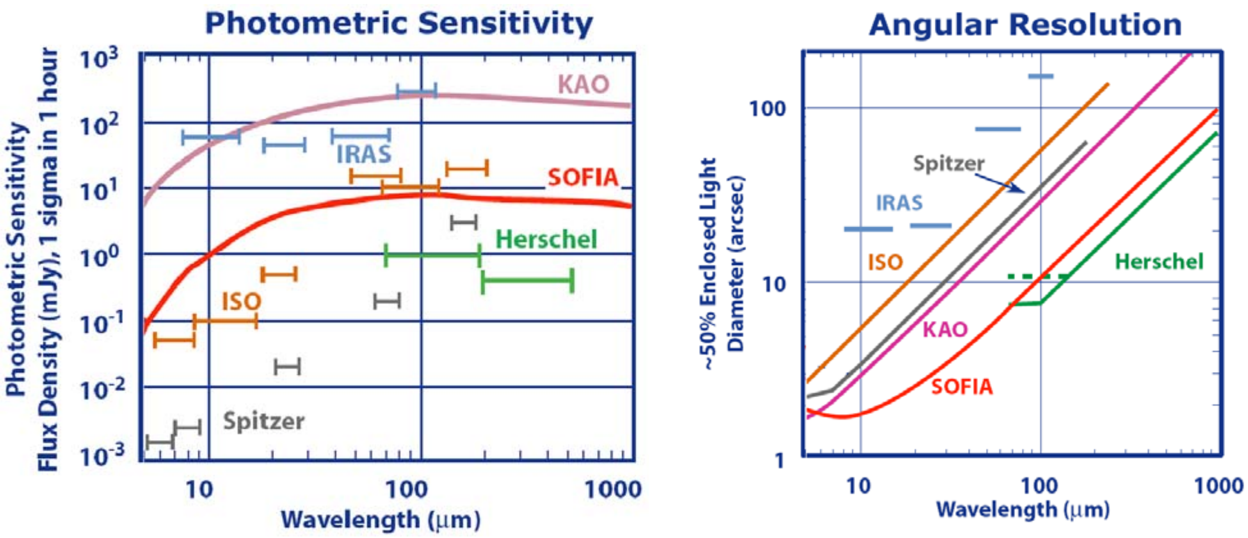

Fig. 4.SOFIA’s photometric sensitivity (**left**) will be comparable to that of the space IR observatory ISO and its high angular resolution (**right**) will make it the premier IR imaging facility for the next two decades

4.1 SOFIA and Spitzer

SOFIA will become operational near the time that Spitzer runs out of liquid helium (Figure 5). The science impact of SOFIA not being contemporary with the Spitzer cryogenic mission is small: Spitzer is a high sensitivity imaging and low resolution spectroscopy mission. SOFIA is a high spectral and high angular resolution mission.

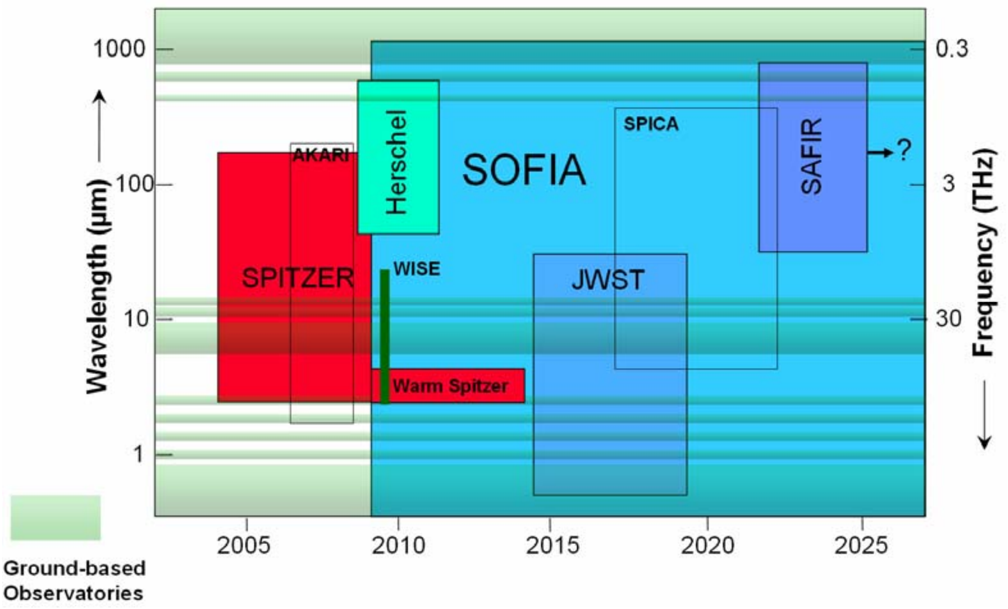

Fig. 5. SOFIA's flight lifetime and time-frame will make it the premier facility for doing far-IR and submillimeter wave astronomy from 2010 until the mid 2030s.. It will be the only facility available for wavelength coverage in the 25-1200 μm spectral region and for high resolution spectroscopy during 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.

As it now stands, the two observatories are very complementary and when Spitzer runs out of liquid helium in early FY09, SOFIA will be the only observatory working in the 25 to 60 micron region until the SAFIR mission flies. SOFIA will be available to complement and supplement the Spitzer warm mission during 2009-2014.

4.2 SOFIA and Herschel

Herschel and SOFIA are both critically important and complementary missions that will now start at about the same time. Joint calibration work for the two missions is currently in progress. Even during the years of overlap of the two missions, SOFIA will be the only program with imaging and spectroscopic capabilities in the 25 to 60 μm spectral region and with high resolution spectroscopic capability in the 60 to 150 μm spectral region (see Figure 6). When

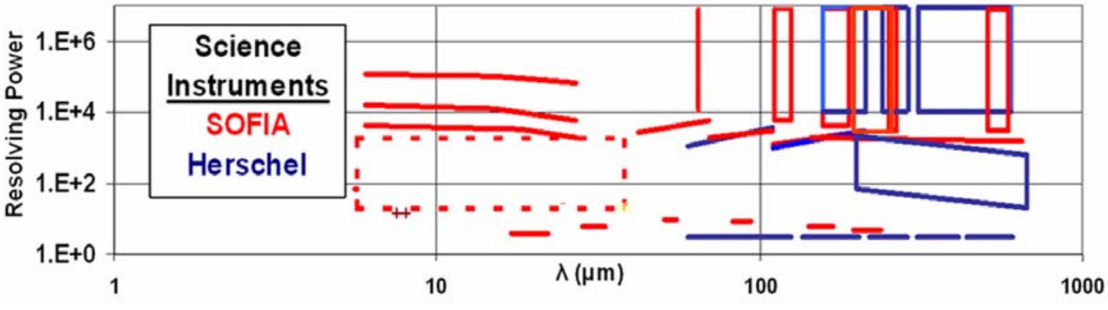

Fig. 6. SOFIA and Herschel spectral resolution and wavelength coverage compared.

Herschel's cryogen supply is exhausted in ~2011, SOFIA will be the only NASA mission operating in the 25 to 600 µm region for many years. SOFIA will be the facility of choice for imaging and spectroscopic follow-up of many of Herschel's discoveries. Future generations of advanced instrumentation will give SOFIA unique capabilities to follow-up Herschel discoveries using such techniques as polarimetry, heterodyne array imaging, and heterodyne spectroscopy of the ground state of molecular hydrogen at 28 µm and of other interesting astrophysical lines.

4.3 SOFIA and JWST

SOFIA will be scientifically highly complementary to NASA's James Webb Space Telescope (JWST) Mission that is expected to be launched in 2013. Before JWST is deployed and after Spitzer's liquid helium runs out, SOFIA will be the only mission capable of observing in the 5 to 8 µm spectral region, where there are important organic chemical signatures. Even after JWST is launched, SOFIA is the only mission that will be capable of providing complementary observations beyond 28 µm and high resolution spectroscopy in 5 to 28 µm region.

4.4 SOFIA and WISE

WISE is a very sensitive survey that will image the entire sky at wavelengths of 3.3, 4.7, 12, and 23 µm with a plate-scale of 2.75 arcseconds per pixel. It is expected that WISE will be launched in November of 2009, just as SOFIA begins initial science operations. SOFIA can provide many important follow up observations of WISE discoveries. 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 discovered by WISE but not seen by IRAS. Nearby cold Brown Dwarfs discovered by WISE can be measured spectroscopically using FLITECAM in GRISM mode and EXES.

5. SOFIA SCIENCE: AN OBSERVATORY WITH OPPORTUNITIES FOR EVERYONE

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 the nature of nearby galaxies.

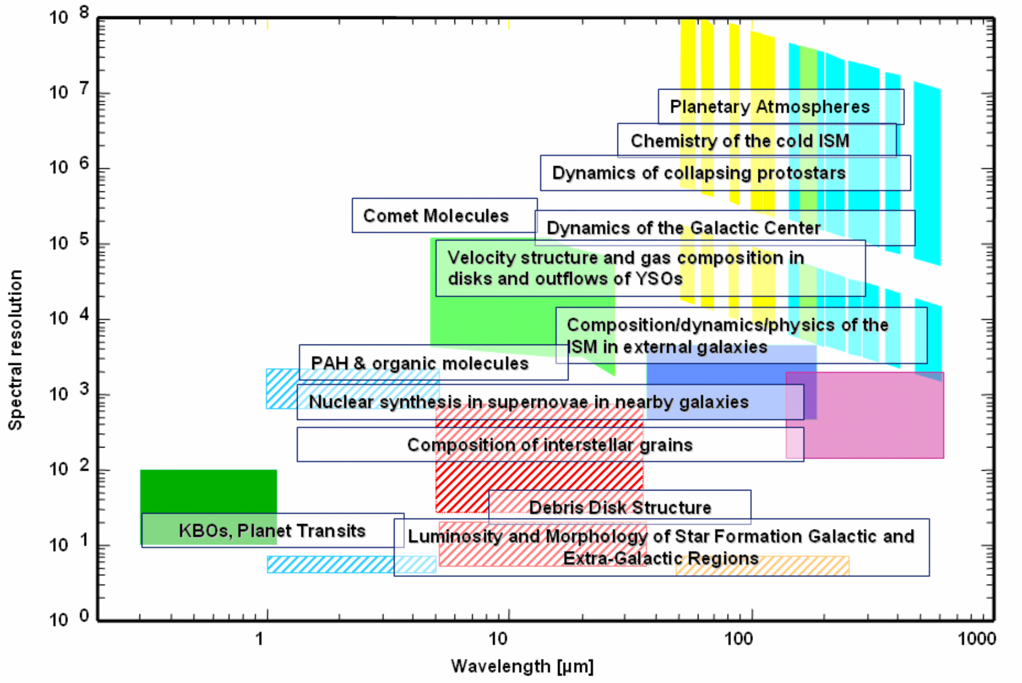

Fig. 7. The same plot as in Fig. 3 with the science topics overlaid in the appropriate positions.

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 submillimeter 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 the universe. We illustrate in Fig. 7 how SOFIA, with its broad range of wavelength and spectral resolution coverage, will be able to attack a diverse array of science topics. Among the science topics that SOFIA will be able to address are: the characteristics of dwarf planets at the edge of our Solar System, the death of stars whose ashes enrich the chemical content of the galaxies, and the study of the black hole and associated star formation in the center of our galaxy. Below, we discuss in more detail some of the science problems that we expect will be studied with SOFIA during the early years of its mission.

5.1 Exploring the Kuiper Belt with Stellar Occultations

Pluto and many other newly defined Dwarf Planets in and beyond the Kuiper Belt represent some of the oldest material known in the solar system. They inhabit the region beyond the orbit of Neptune. Knowledge of their fundamental properties is essential to our understanding of the origin and early evolution of the outer solar system. Stellar occultations probe Dwarf Planets with a spatial resolution of a few kilometers. From these 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 ground-based observatories. A large, mobile telescope like SOFIA that can fly into the shadow of an occultation (see Figure 8) 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.[6]

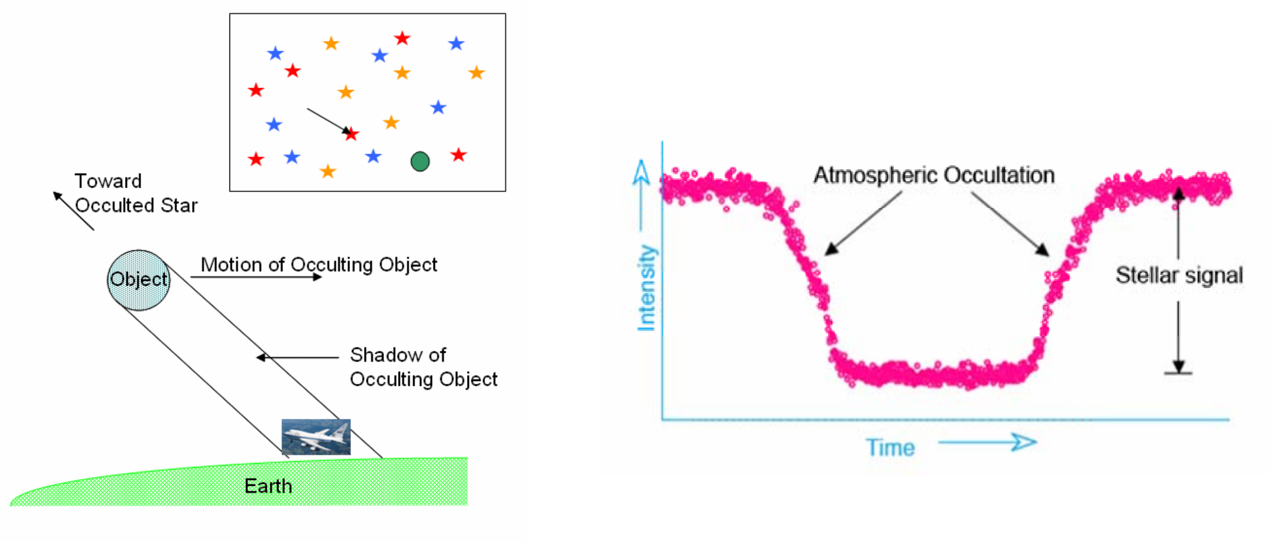

Fig. 8. Occultation studies with SOFIA will probe the sizes, atmospheres, and possible satellites of newly discovered planet-like objects in the outer Solar system. **Left**) SOFIA can fly directly into the shadow of an occultation, making available hundreds of events per year compared to the handful accessible with ground-based observatories. **Right**) Pluto occultation light curve observed on the KAO (1988) probes the atmosphere. NASA images.

5.2 Precise Photometry of Extra-Solar Planet Transits

SOFIA will fly above most of the scintillating component of the Earth's atmosphere and can therefore be expected to yield very precise and stable photometric measurements of stars. Thus, we anticipate that very high quality data on transits of extra-solar planets can be obtained with SOFIA using HIPO and FLITECAM (see Figure 9). Precise photometric observations of transiting extra-solar planets can 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.[7]

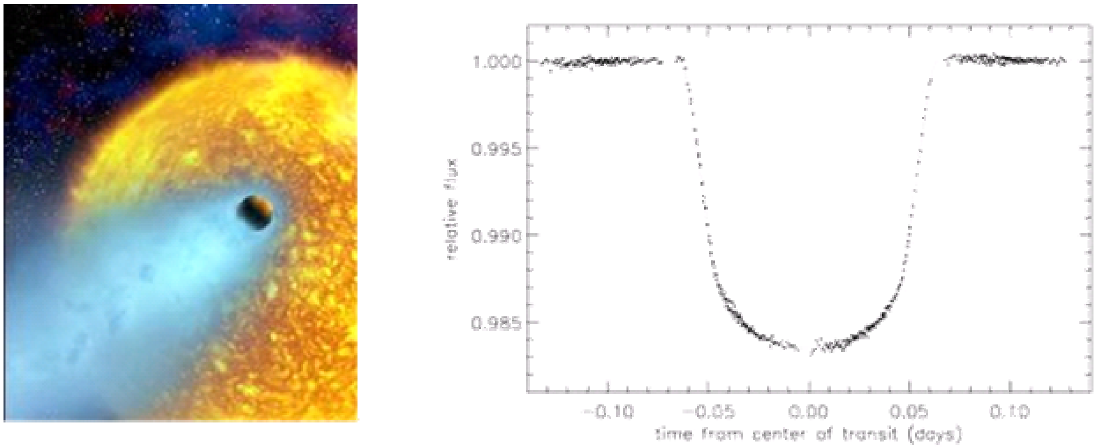

Fig. 9. SOFIA, flying above the scintillating component of the atmosphere, will be the most sensitive freely pointing observatory for extra-solar planetary transits after HST. Above are an artist's concept (**left**) and HST STIS data (**right**) showing the transit of a large extra-solar planet transiting across the face of its star, HD 209458. NASA images.

5.3 Water in Planet-Forming Disks

Angular momentum conservation during the collapse phase will cause proto-stars to be surrounded by circumstellar (CS) gaseous disks[8] 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. 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 sublimation temperature of water ice (170K). [9] The origin and distribution of water in the inner proto-planetary disks has is crucial to our understanding of the abundance of water on terrestrial planets in the habitable zones around stars (see Figure 10).

Previous observational studies of planet-forming systems have focused exclusively on the mid-IR continuum spectrum that is dominated by thermal emission by dust in the disk because detection of molecular emission lines from the gas is difficult with present instrumentation.[10] 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 to 2.4 μm window have revealed the power of such molecular line studies, but these are of course limited to very hot gas close to the protostar. 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 submillimeter wavelengths) are hampered by either severe beam dilution or by telluric absorption.

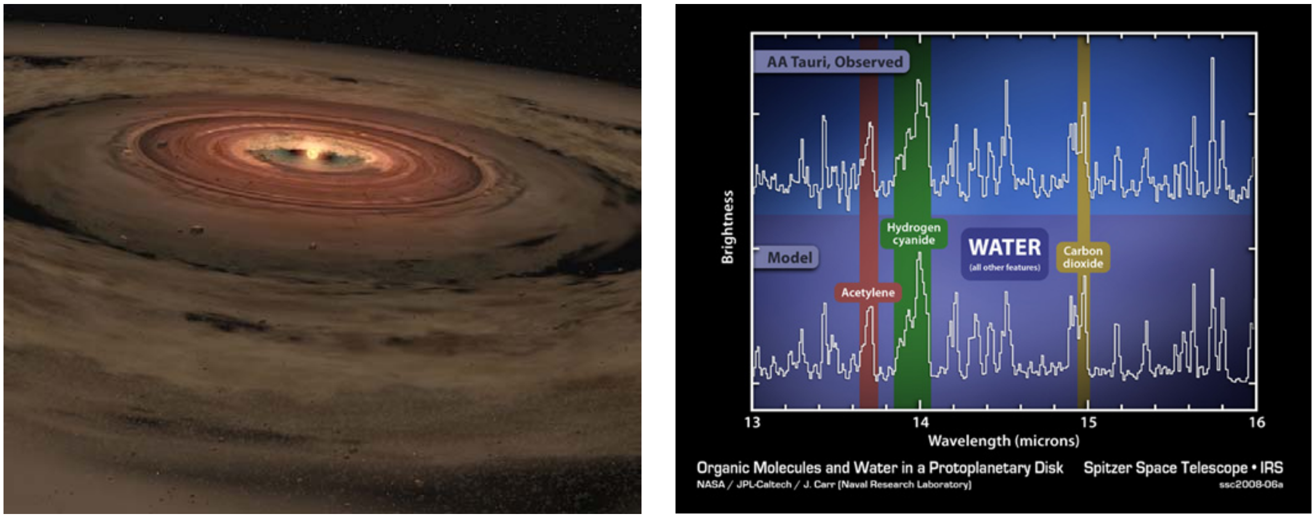

Fig. 10. Water and organic molecules in proto-planetary disks. **Left**) Artist's conception of a young star encircled by a proto-planetary disk, and **right**) NASA Spitzer Space Telescope spectra of a proto-planetary disk revealing the signatures of H_2O vapor, CO_2, HCN, and acetylene—some of the basic building blocks of life. NASA/JPL-Caltech/J. Carr, NRL.

5.4 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 Figure 11. The formation of new stars slowly consumes 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

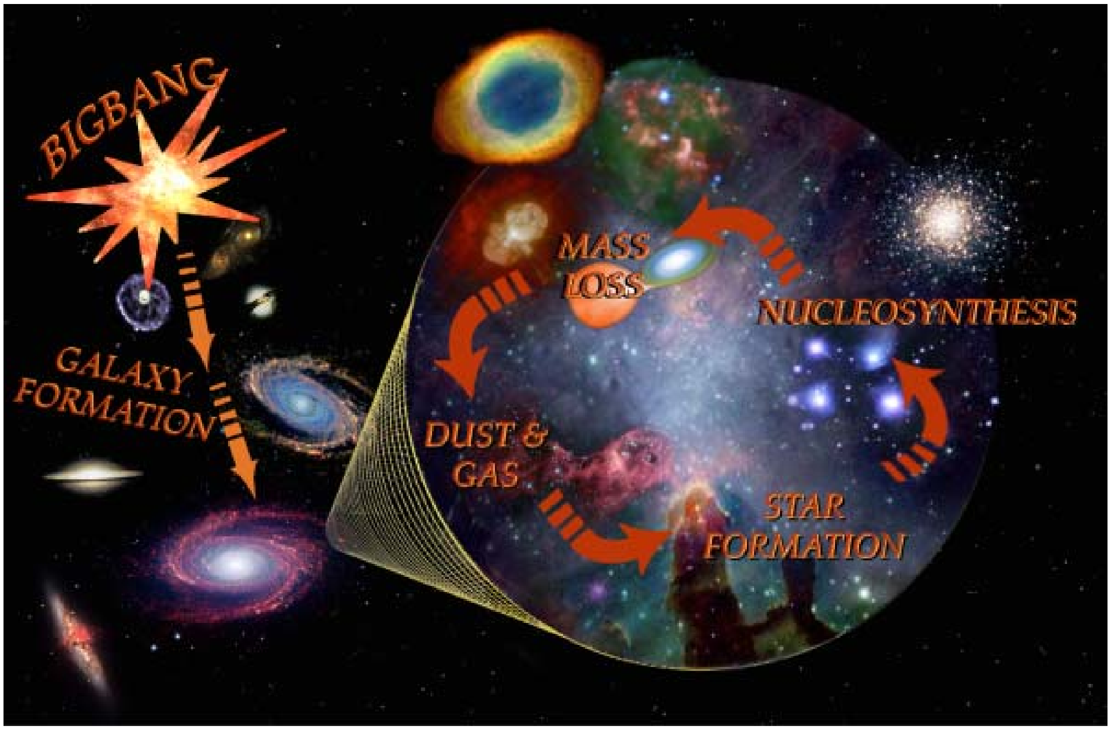

Fig. 11 Chemical Evolution of the universe. After Gehrz 2008.[14]

explosive nucleosynthesis into the ISM, slowly increasing its metallicity. This constant recycling and the associated enrichment drives 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 of these processes 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.

FLITECAM, FORCAST, and HAWC will provide detailed, broad/narrow band studies of the spectral energy distributions of active regions of star formation and known stellar death sites such as supernova remnants, 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] at 63 and 145 µm and of [C II] at 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.

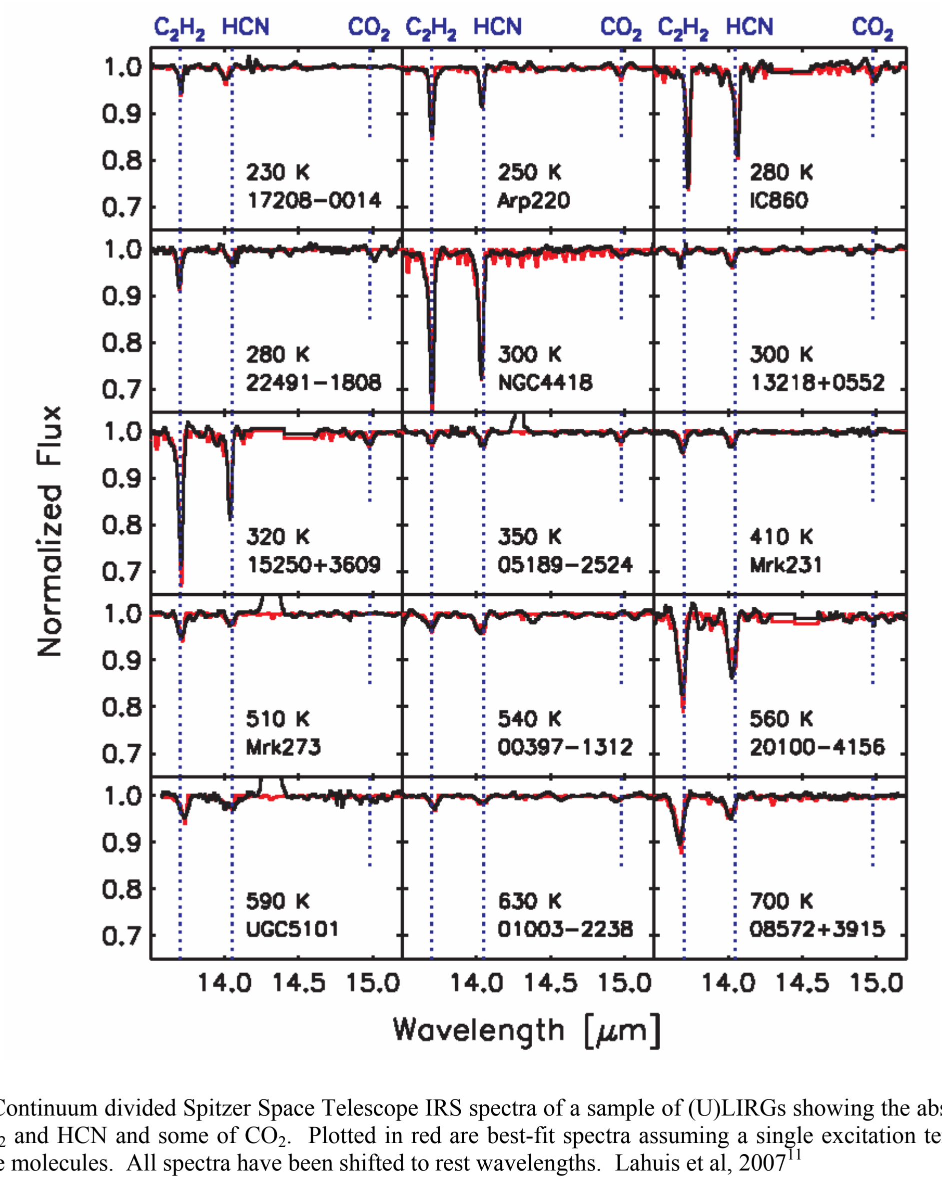

Fig. 12. Continuum divided Spitzer Space Telescope IRS spectra of a sample of (U)LIRGs showing the absorption bands of C_2H_2 and HCN and some of CO_2. Plotted in red are best-fit spectra assuming a single excitation temperature for all three molecules. All spectra have been shifted to rest wavelengths. Lahuis et al, 2007[11]

A particularly relevant example of how IR spectra can be used to study the star formation process in external galaxies is shown in Figure 12. Here, low-resolution Spitzer Space Telescope IRS spectra toward a sample of deeply obscured (U)LIRG nuclei 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} cm^{-2}. Lahuis et al.[11] 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.

5.5 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 during the chemical evolution of the universe by the cycle of stellar evolution (see Figure 11). Deuterium is thus potentially a key element for probing the origin and evolution of the universe as well as the star formation history of the universe. As pointed out by Neufeld et al.[12], 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 dipole pole moment that essentially compensates for the higher abundance of molecular hydrogen.

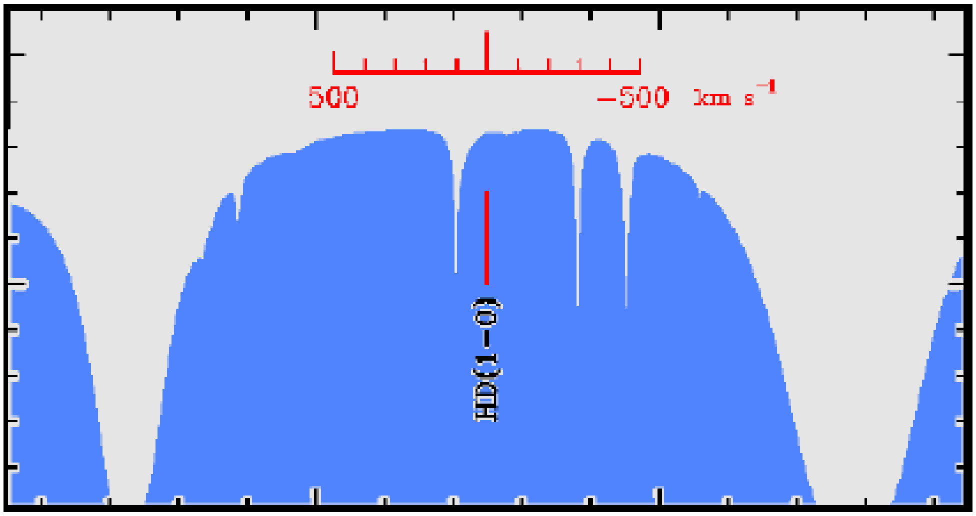

Fig. 13. Atmospheric transmission around the 112 µm HD line at 40,000 feet

Measuring the amount of cold HD (T<50K) 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 (Figure 13). The 3 THz (100 µm) channel on GREAT 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.[13] In the future, HD mapping could be used to map out the cold molecular gas component of galaxies much in the way 21cm mapping is used to map out the neutral hydrogen (HI) component.

5.6 Nucleosynthesis in Classical Nova Explosions

The astrophysical thermonuclear runaways that produce classical nova explosions may play an important part in producing some of the isotopic anomalies that are present in the meeteoritic and cometary debris that represent the remains of the primitive solar system. Gehrz[14] has reviewed the use of IR observations to quantify the physical parameters of classical nova outbursts and to assess their contribution to the chemical abundances in the ISM where star formation occurs. Metal 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.

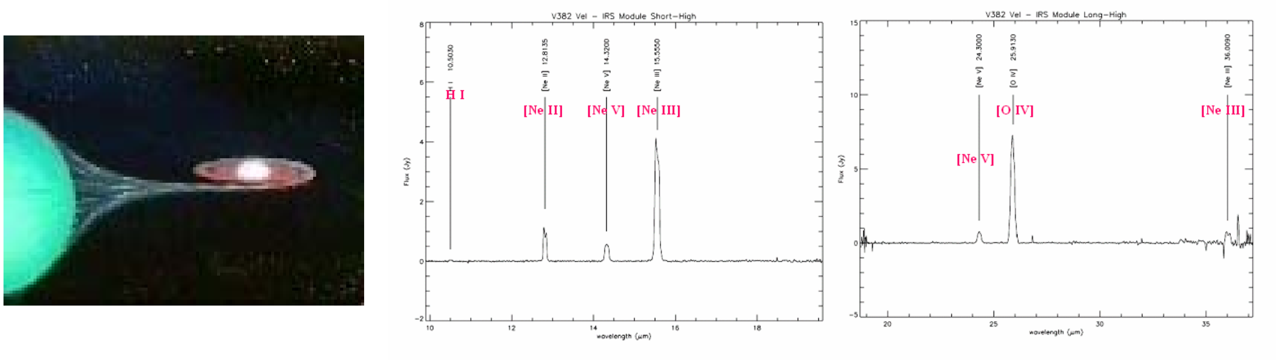

Fig. 14 **Left**) Nova explosions caused by thermonuclear runaways on the surfaces of white dwarfs accreting matter in close binary systems lead to the production of Ne and O as shown (**right**) in Spitzer Space Telescope IRS Short and Long-High Resolution Spectra. Abundances and kinematics can be determined from the spectra. Left panel from R. Narayan et al. (CfA), ASCA, ISAS, NASA; data from NASA/JPL/Caltech/R. D. Gehrz

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. SOFIA's ability to observe objects close to the sun by flying a path that places the sun below the horizon will enable a continuous record of the temporal development of such events to be recorded. Second, the spectroscopic capabilities of SOFIA will enable the recording of many forbidden lines obscured by the atmosphere from ground-base 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 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 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), [Si II] (34 μm), and [S I] (26 μm) and [S III] (18.7 μm). Numerous forbidden neon lines in obscured spectral regions are also available to SOFIA.

5.7 The Black Hole and Circumnuclear Disk at the Galactic Center

A $4x10^6$ $M_\odot$ black hole has been shown to exist in the core of the Milky Way.[15, 16] SOFIA, with eight relevant instruments, will be very well suited to study the material falling into the black hole and make observations of the emission from the circumnuclear disk region surrounding it.

The circumnuclear disk (CND) orbiting the super-massive black hole at the Galactic Center at a distance of 1 to 5 parsecs holds the key to understanding the 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.[17] For example, high resolution spectroscopy using EXES, FIFI-LS, GREAT, and CASIMIR will provide a powerful probe of the physical conditions (eg., density and temperature), ionization state, energetics, mass, and kinematics of the gas through studies of the pure rotational H_2 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 (eg., J = 14 - 13).

5.8 General Capabilities of SOFIA's Far Infrared and Submillimeter Array Detectors

Using the first light heterodyne instruments, astrophysical spectral line surveys will reveal many new molecular and atomic lines in the broad atmospheric window of SOFIA. With spectral line sensitivities similar to those now being achieved at the Caltech Submillimeter Observatory (CSO), many new lines should be observed for the first time. Using the far-IR cameras, Galactic plane mapping will reveal structure never before observed at these wavelengths. Regions of high-mass and low-mass star formation can be imaged at 38, 53, 88, 155, and 215 µm with unprecedented high spatial resolution.

6. PARTNERSHIP OPPORTUNITY ON SOFIA

Currently, NASA is funding 80% of the operations phase of the SOFIA Program and the German space agency, DLR, is funding 20%. 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.

7. 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 submillimeter spectral regions for the next twenty years. With the ability to deploy new and updated instruments, the observatory will play an important role in a variety of astrophysical problems well into the first third of the 21st century.

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