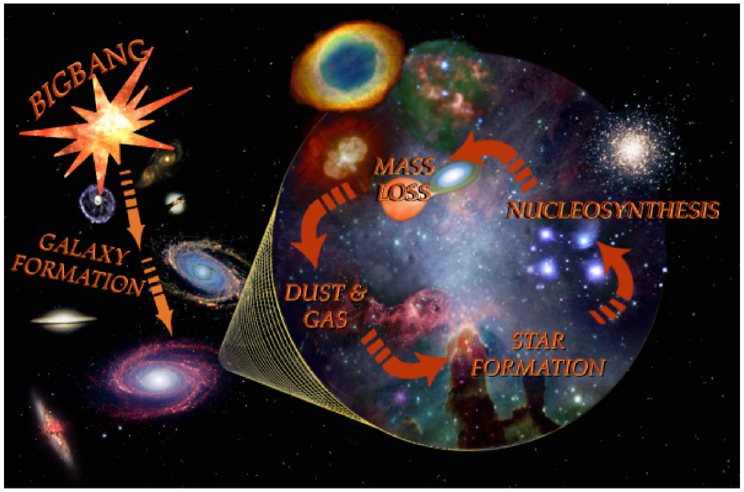
The Stratospheric Observatory for Infrared Astronomy (SOFIA)



R. D. Gehrz

Lead, SOFIA Community Task Force

Department of Astronomy, University of Minnesota

http://www.sofia.usra.edu

University of Heidelberg, Heidelberg, Germany, May 19, 2009

Outline

- *SOFIA Heritage and Context*
- *SOFIA Description and Status Report*
- *SOFIA Performance Specifications*
- *SOFIA's New Science Vision*
- *SOFIA Schedule and Opportunities for Collaboration*
- *Summary*

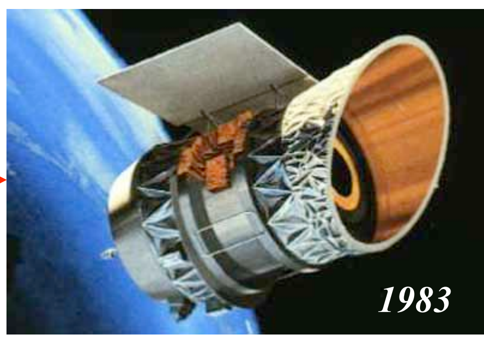
The History of Flying Infrared Observatories

Science objectives

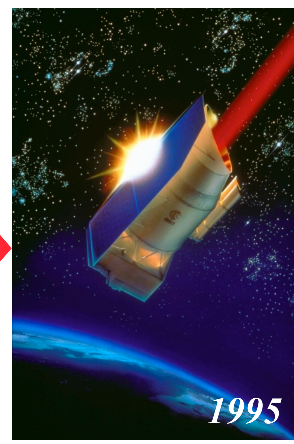
NASA Lear Jet Observatory

NASA Kuiper Airborne Observatory (KAO)

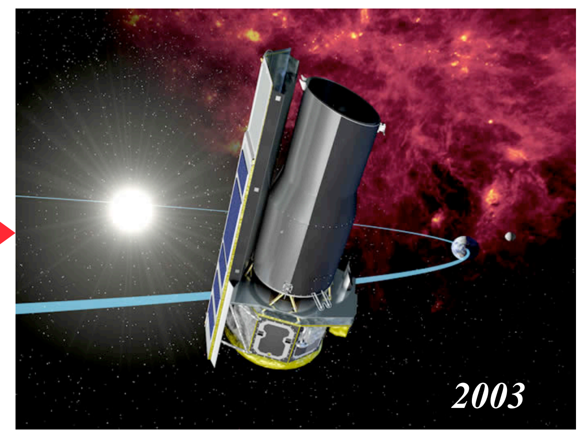
NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)



NASA Infrared Astronomical Satellite (IRAS)

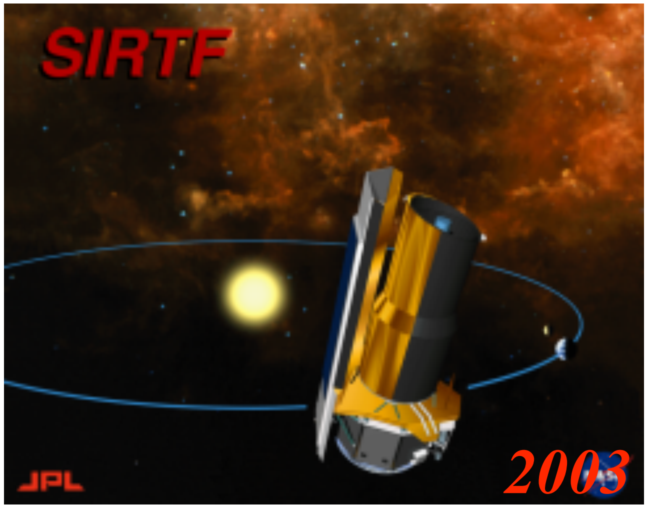


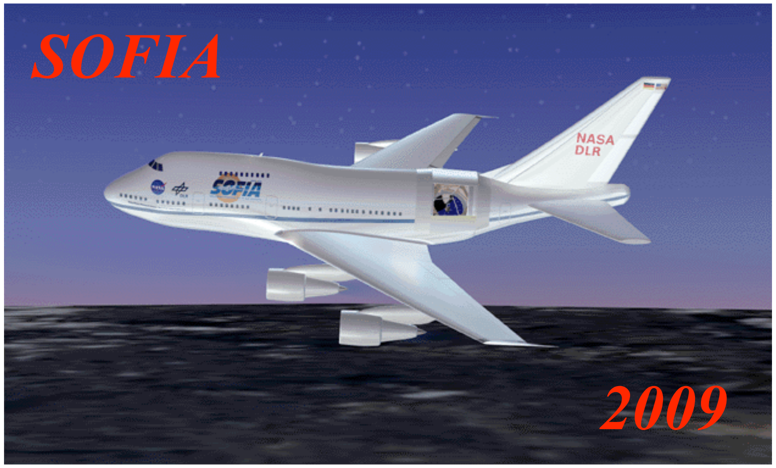
ESA Infrared Space Observatory (ISO)

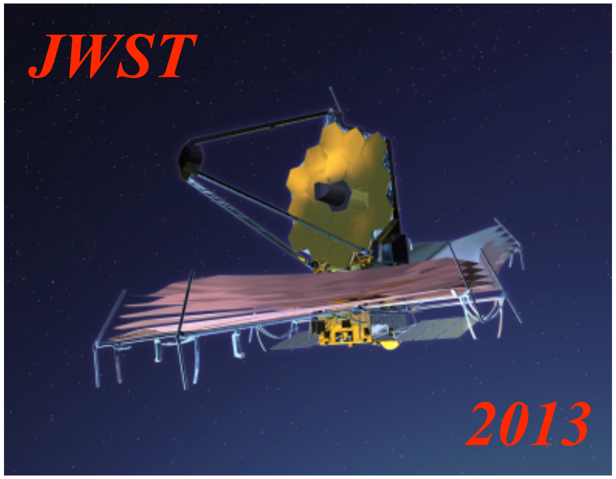


NASA Spitzer Space Telescope

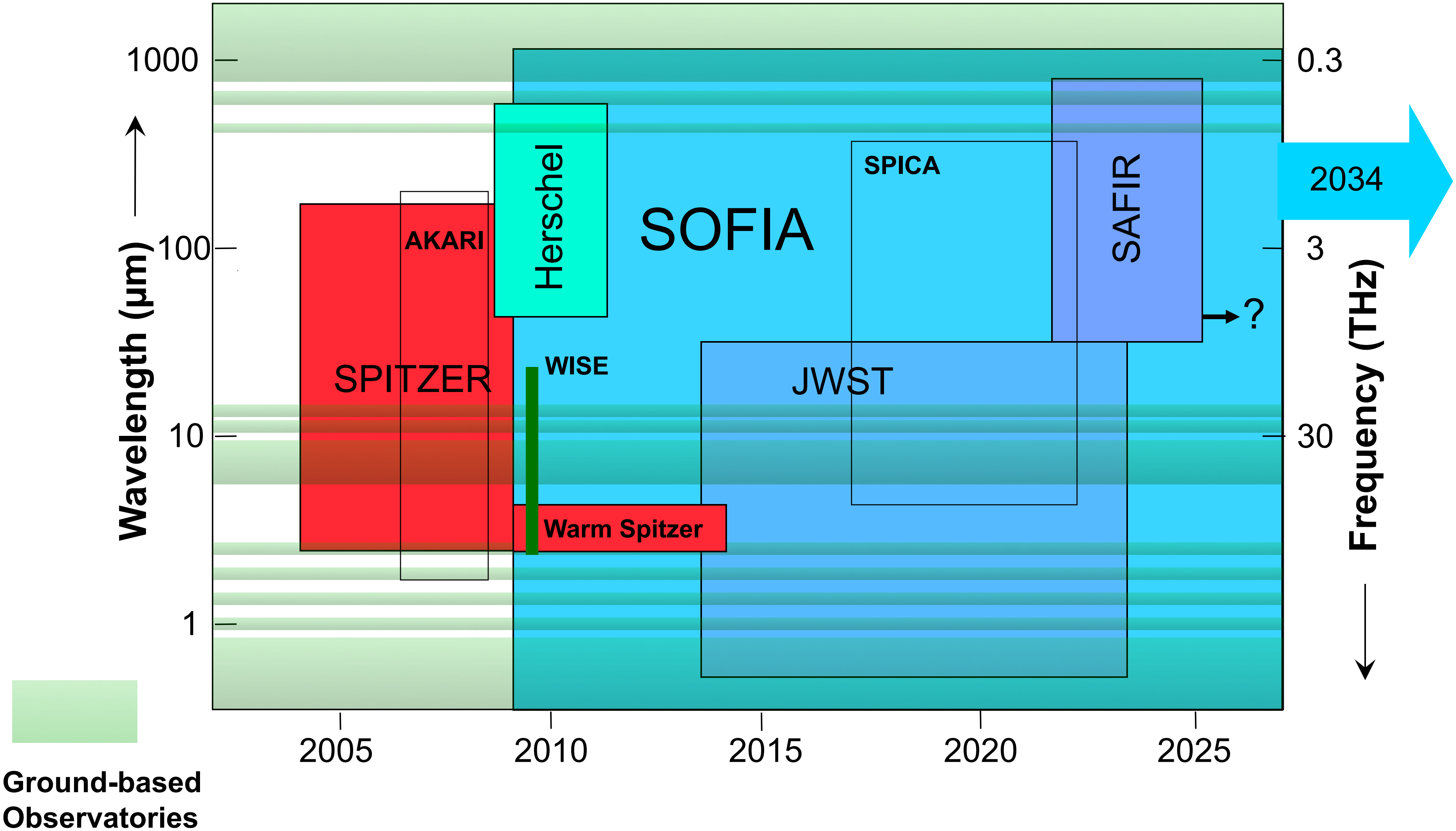
SOFIA and its Companions in Space



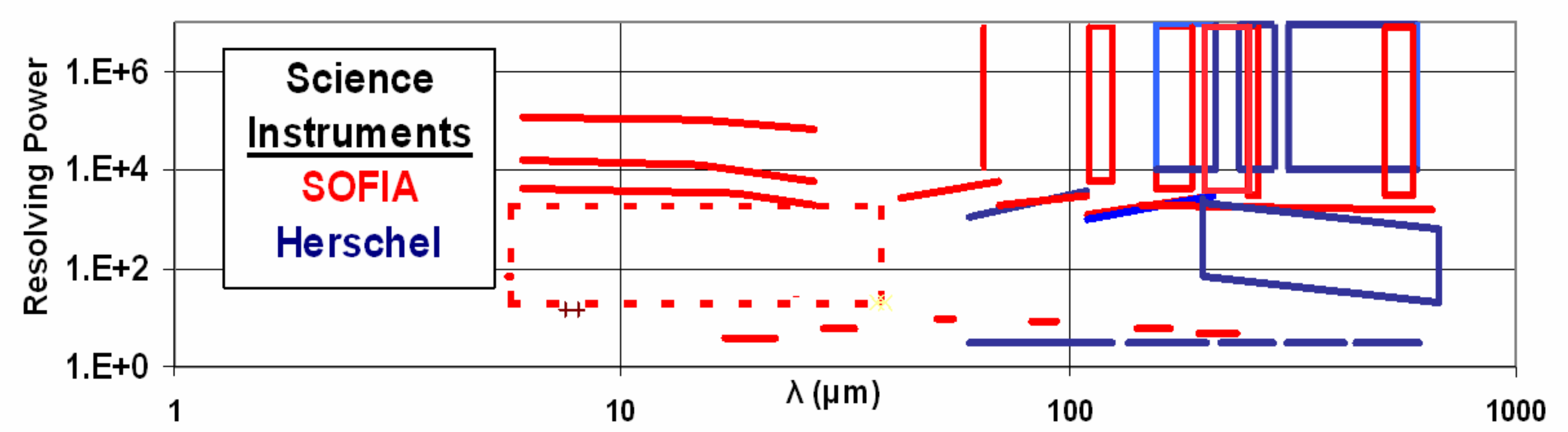




SOFIA and Major IR Imaging/Spectroscopic Space Observatories



SOFIA and Herschel: Complementarity, Synergism



A comparison between SOFIA First Generation SIs and Herschel SIs

- *Similar instrumentation at relatively unexplored long wavelengths*
- *SOFIA will complement and supplement Herschel observations*
- *SOFIA's long life and accessibility will encourage the development and application of new technologies*

SOFIA Mission Overview And Status

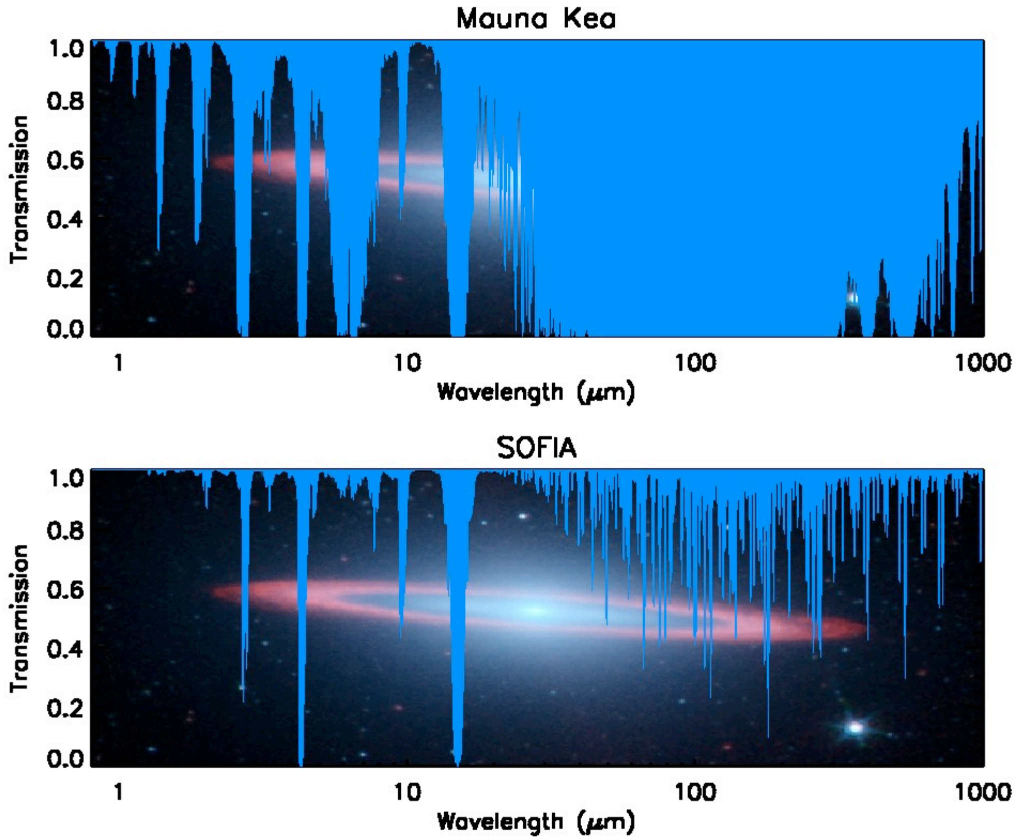
October 29, 2008

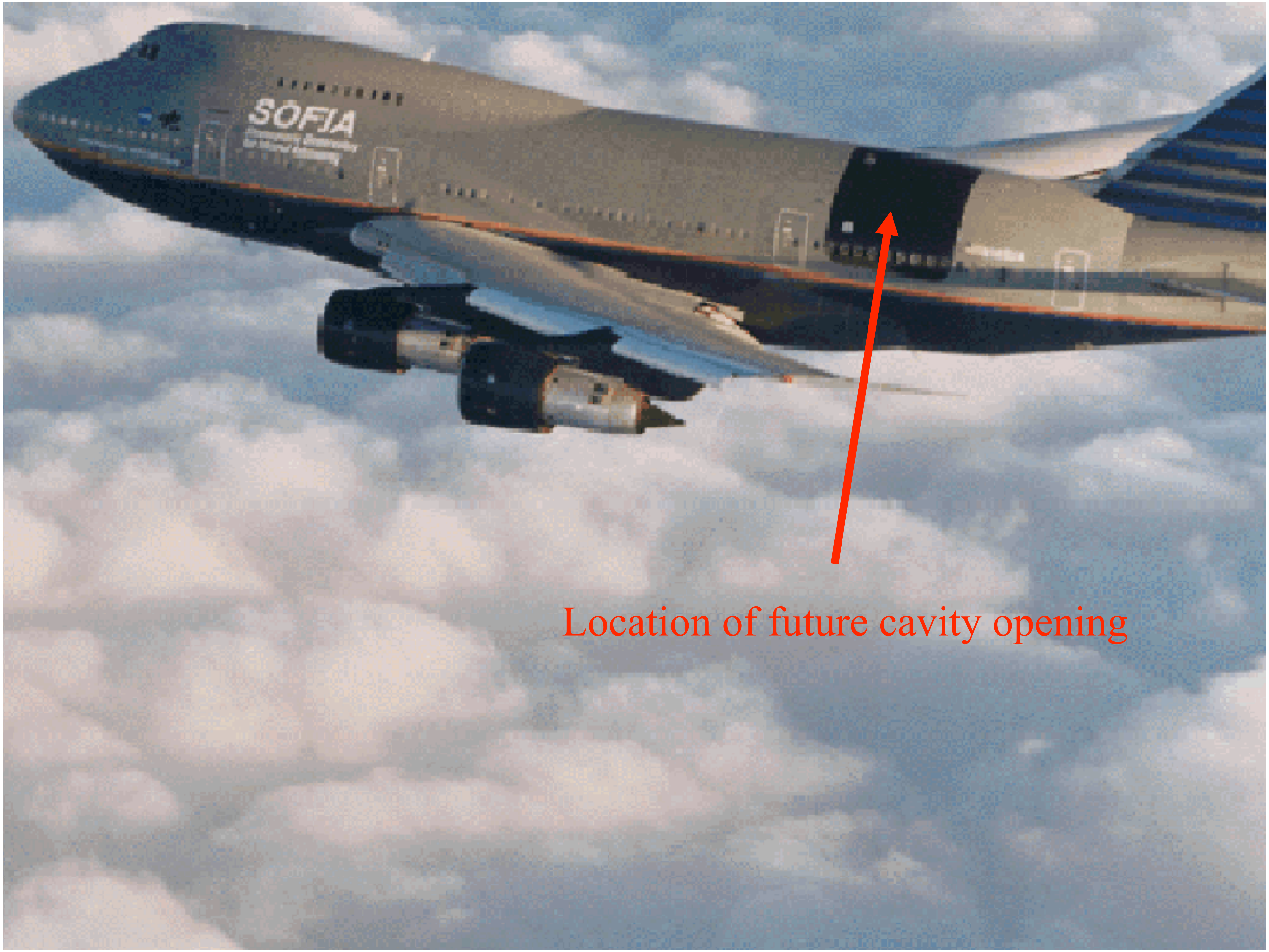
SOFIA Overview

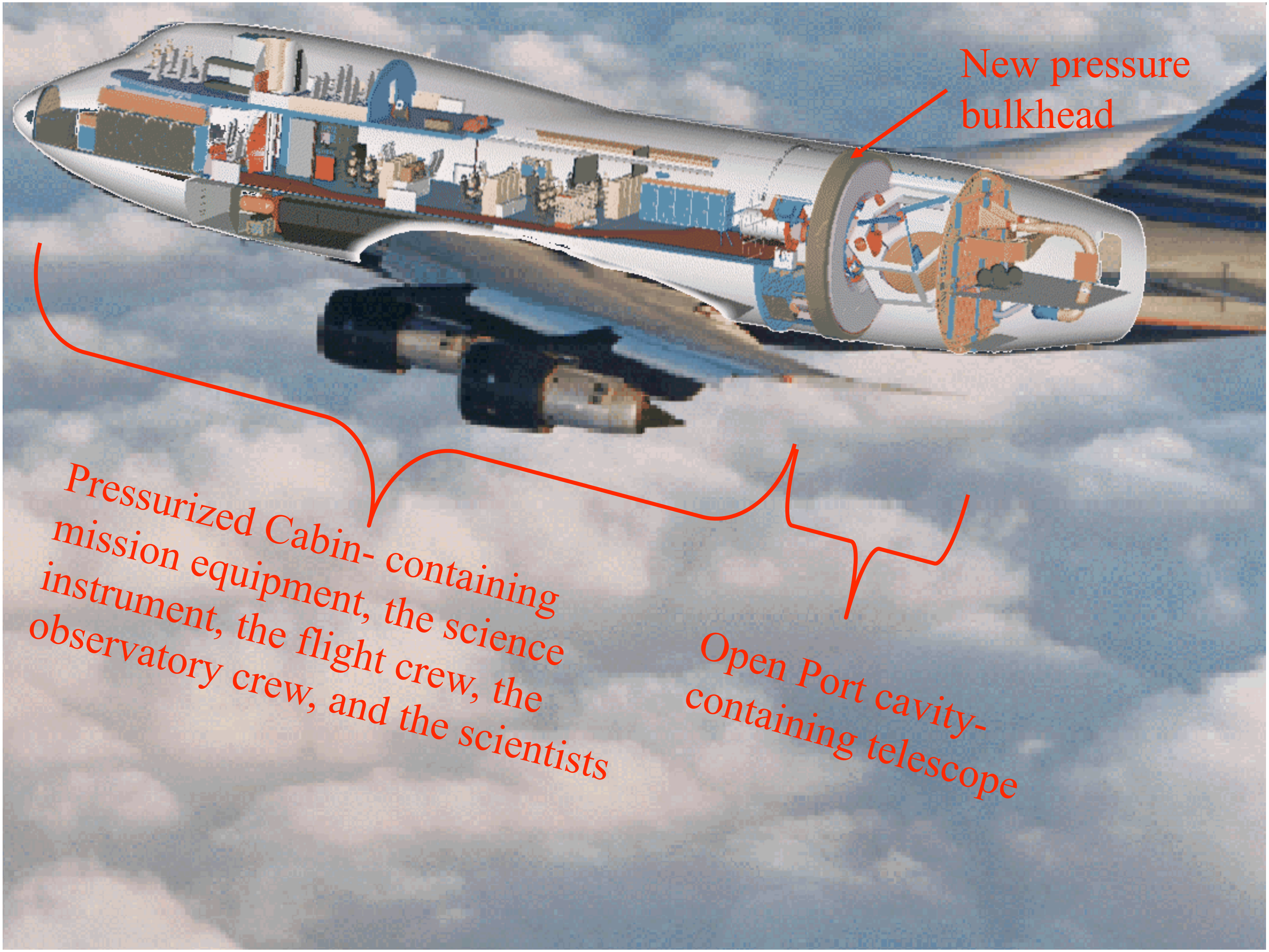
- ***2.5 m telescope in a modified Boeing 747SP aircraft***
  - ***Imaging and spectroscopy from 0.3 μm to 1.6 mm***
  - ***Emphasizes the obscured IR (30-300 μm)***
- ***Service Ceiling***
  - ***39,000 to 45,000 feet (12 to 14 km)***
  - ***Above > 99.8% of obscuring water vapor***
- ***Joint Program between the US (80%) and Germany (20%)***
  - ***First Light in 2009***
  - ***20 year design lifetime –can respond to changing technology***
  - ***Ops: Science at NASA-Ames; Flight at Dryden FRC (Palmdale- Site 9)***
  - ***Deployments to the Southern Hemisphere and elsewhere***
  - ***>120 8-10 hour flights per year***

The Advantages of SOFIA

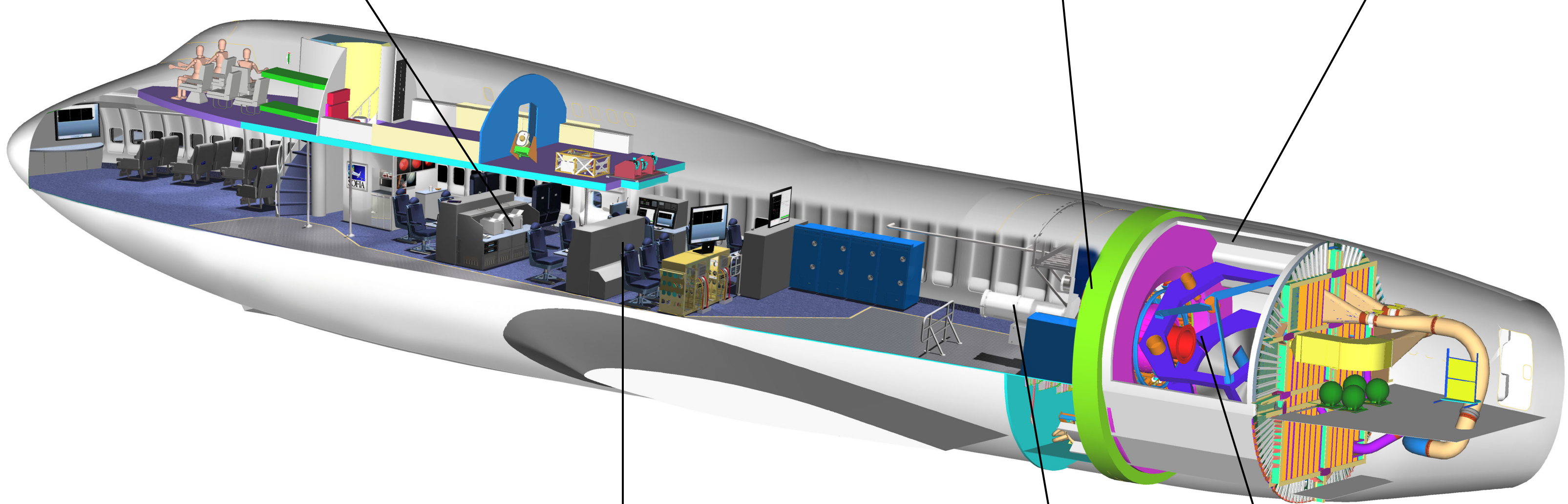
- *Above 99.8% of the water vapor*
- *Transmission at 14 km >80% from 1 to 800 µm; emphasis on the obscured IR regions from 30 to 300 µm*
- *Instrumentation: wide variety, rapidly interchangeable, state-of-the art – SOFIA is a new observatory every few years!*
- *Mobility: anywhere, anytime*
- *Twenty year design lifetime*
- *A near-space observatory that comes home after every flight*




SOFIA
Location of future cavity opening

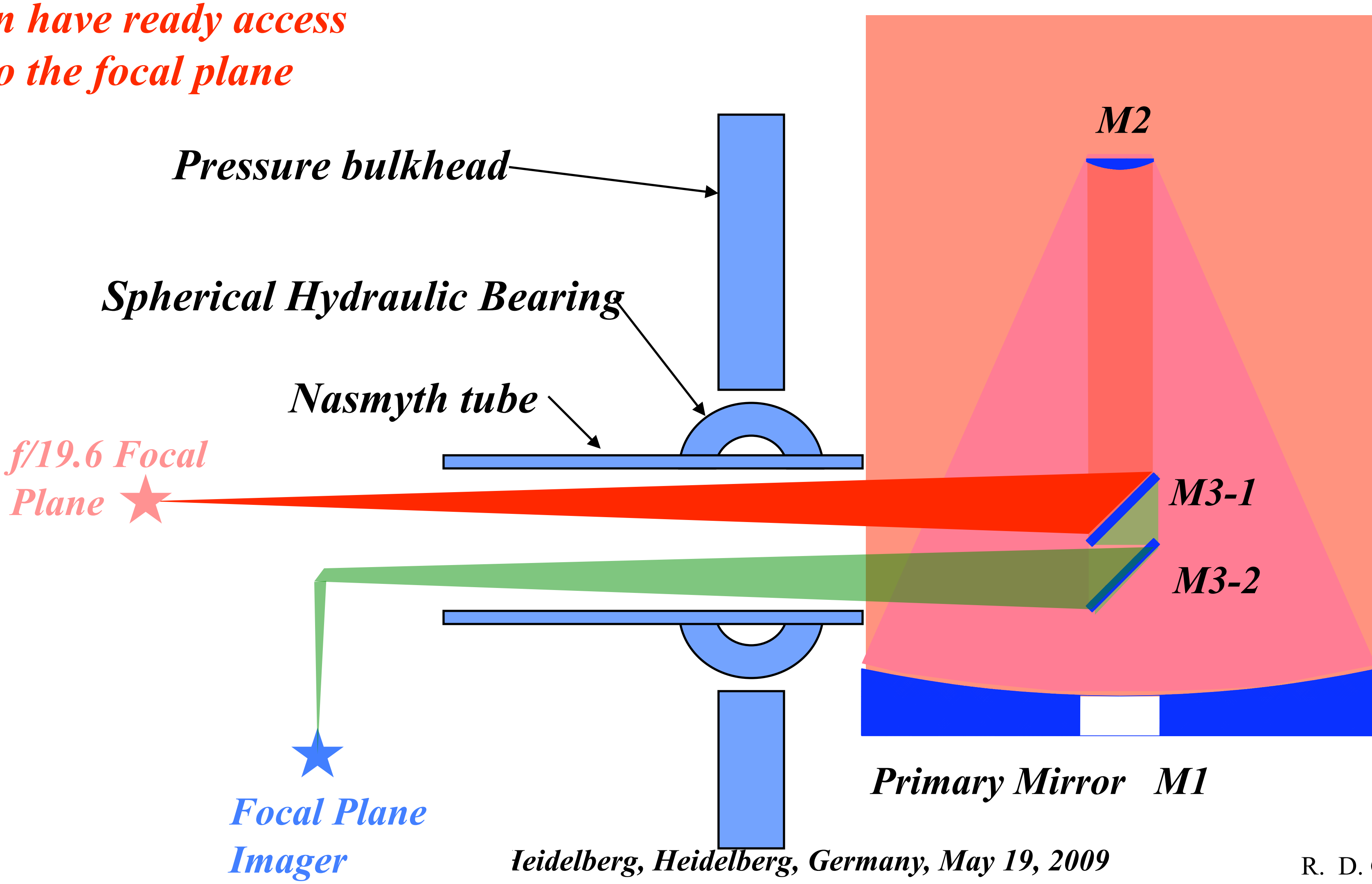

New pressure bulkhead
Pressurized Cabin- containing mission equipment, the science instrument, the flight crew, the observatory crew, and the scientists
Open Port cavity- containing telescope

The SOFIA Observatory

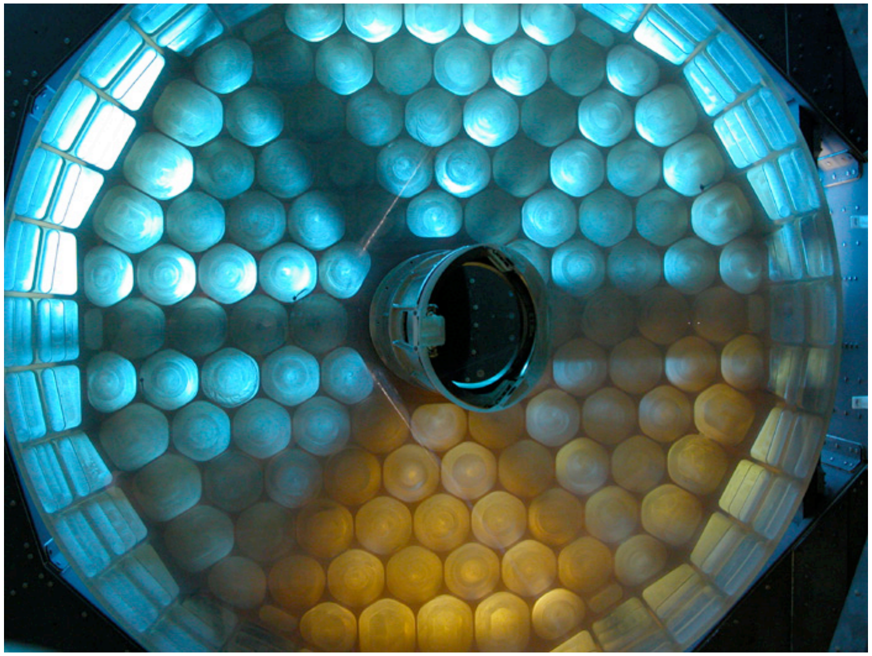


Nasmyth: Optical Layout

Observers in pressurized cabin have ready access to the focal plane



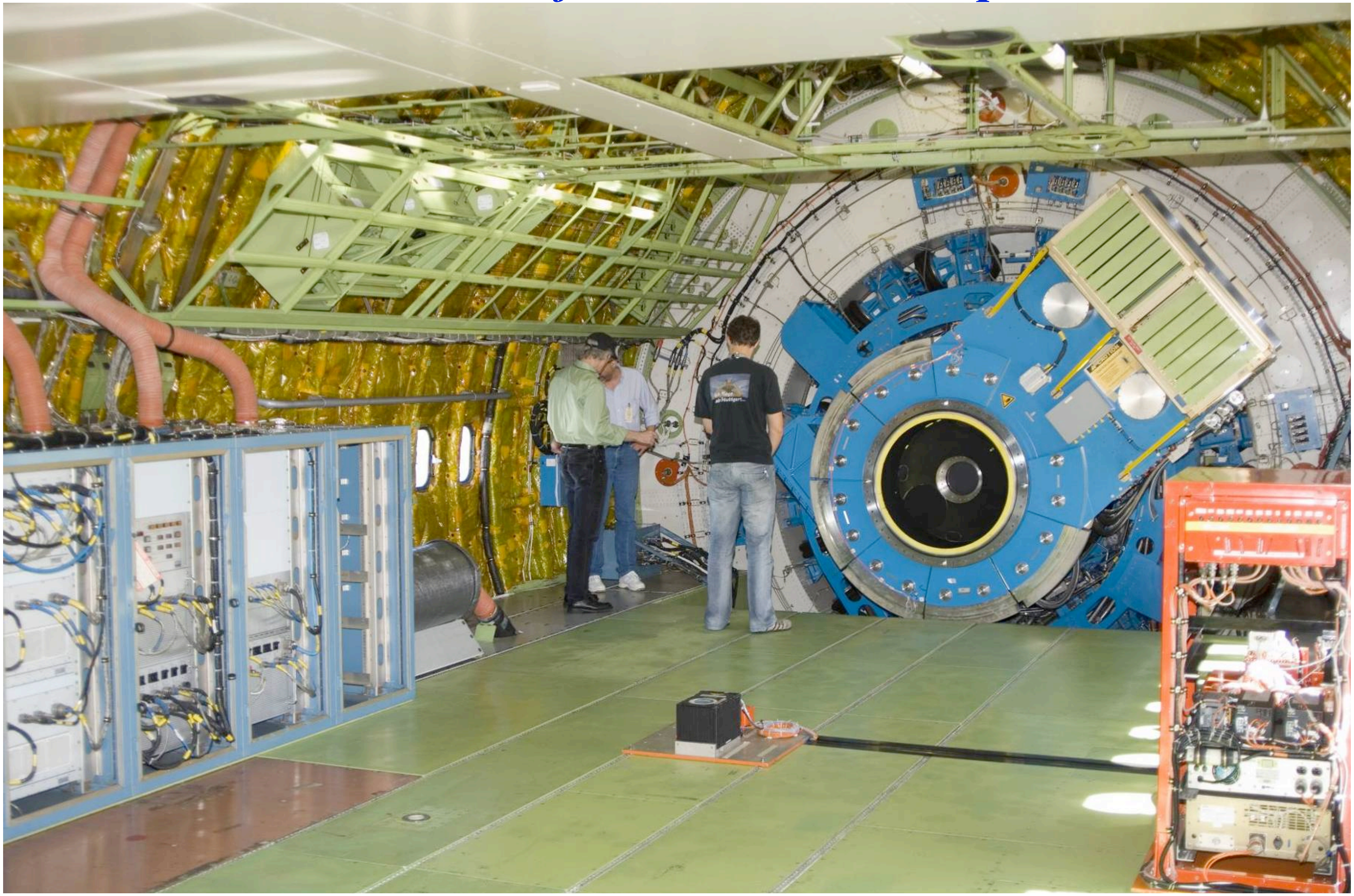
The Un-Aluminized Primary Mirror Installed



Primary Mirror Installed Oct. 8, 2008

hrz

Back End of the SOFIA Telescope



SOFIA Airborne!

Flight.wmv

10 May 2007, L-3 Communications, Waco Texas: SOFIA takes to the air for its second test flight after completion of modifications

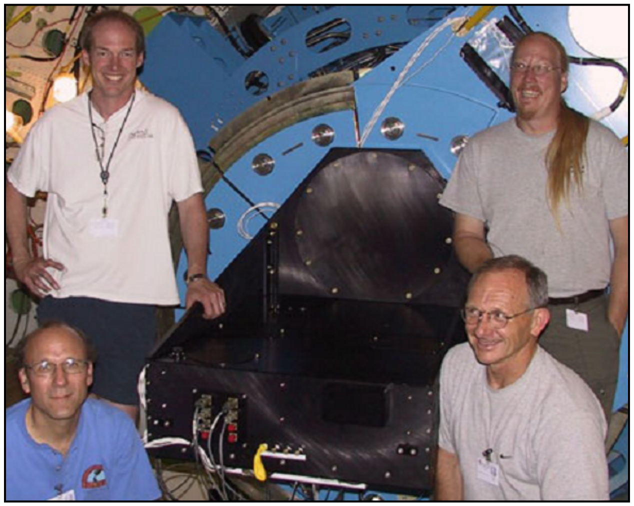
SOFIA's First-Generation Instruments

Instrument	Type	λλ (μm)	Resolution	PI	Institution
HIPO (Available 2010)	fast imager	0.3 - 1.1	filters	E. Dunham	Lowell Obs.
FLITECAM * (Available 2010)	imager/grism	1.0 - 5.5	filters/R~2000	I. McLean	UCLA
FORCAST * (Available 2009)	imager/(grism?)	5.6 - 38	filters/(R~2000)	T. Herter	Cornell U.
GREAT (Available 2009)	heterodyne receiver	62 - 65 111 - 12 158 - 187 200 - 240	R ~ 10^4 - 10^8	R. Güsten	MPIfR
CASIMIR (Available 2011)	heterodyne receiver	250 -264, 508 -588	R ~ 10^4 -10^8	J. Zmuidzinas	Caltech
FIFI LS ** (Available 2009)	imaging grating spectrograph	42 - 110, 110 - 210	R ~1000 - 2000	A. Poglitsch	MPE
HAWC * (Available 2011)	imager	40 - 300	filters	D. A. Harper	Yerkes Obs.
EXES (Available 2011)	imaging echelle spectrograph	5 - 28.5	R ~ 3000 - 10^5	J. Lacy	U. Texas Austin
SAFIRE (Available 2012)	F-P imaging spectrometer	150 - 650	R ~ 1000 - 2000	H. Moseley	NASA GSFC

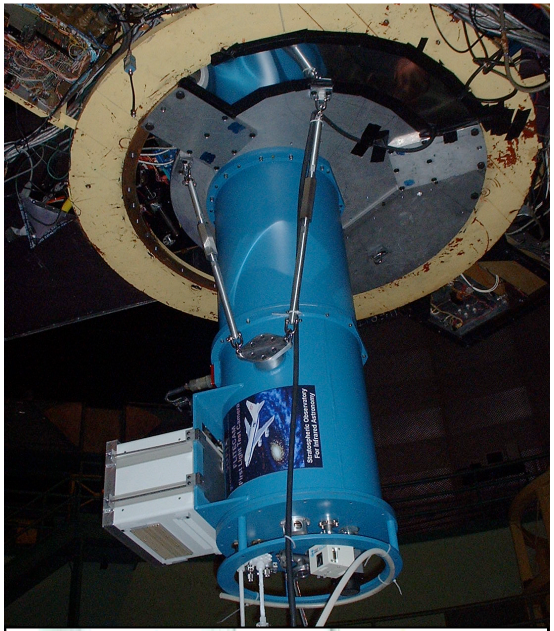
** Facility-class instrument*

*** Developed as a PI-class instrument, but will be converted to Facility-class during operations*

Four First Light Instruments

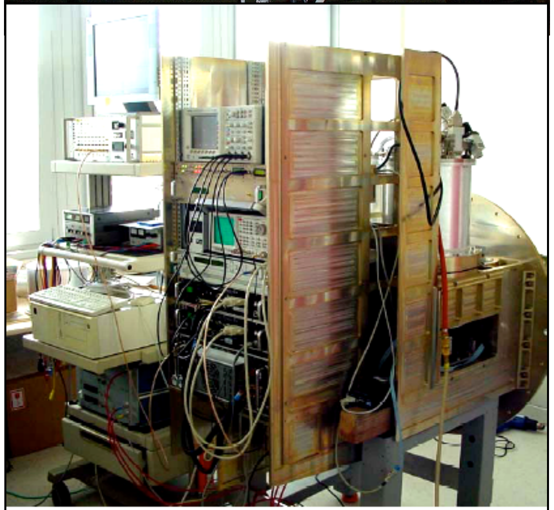


Working/complete HIPO instrument in Waco on SOFIA during Aug 2004



Working/complete FLITECAM instrument at Lick in 2004/5

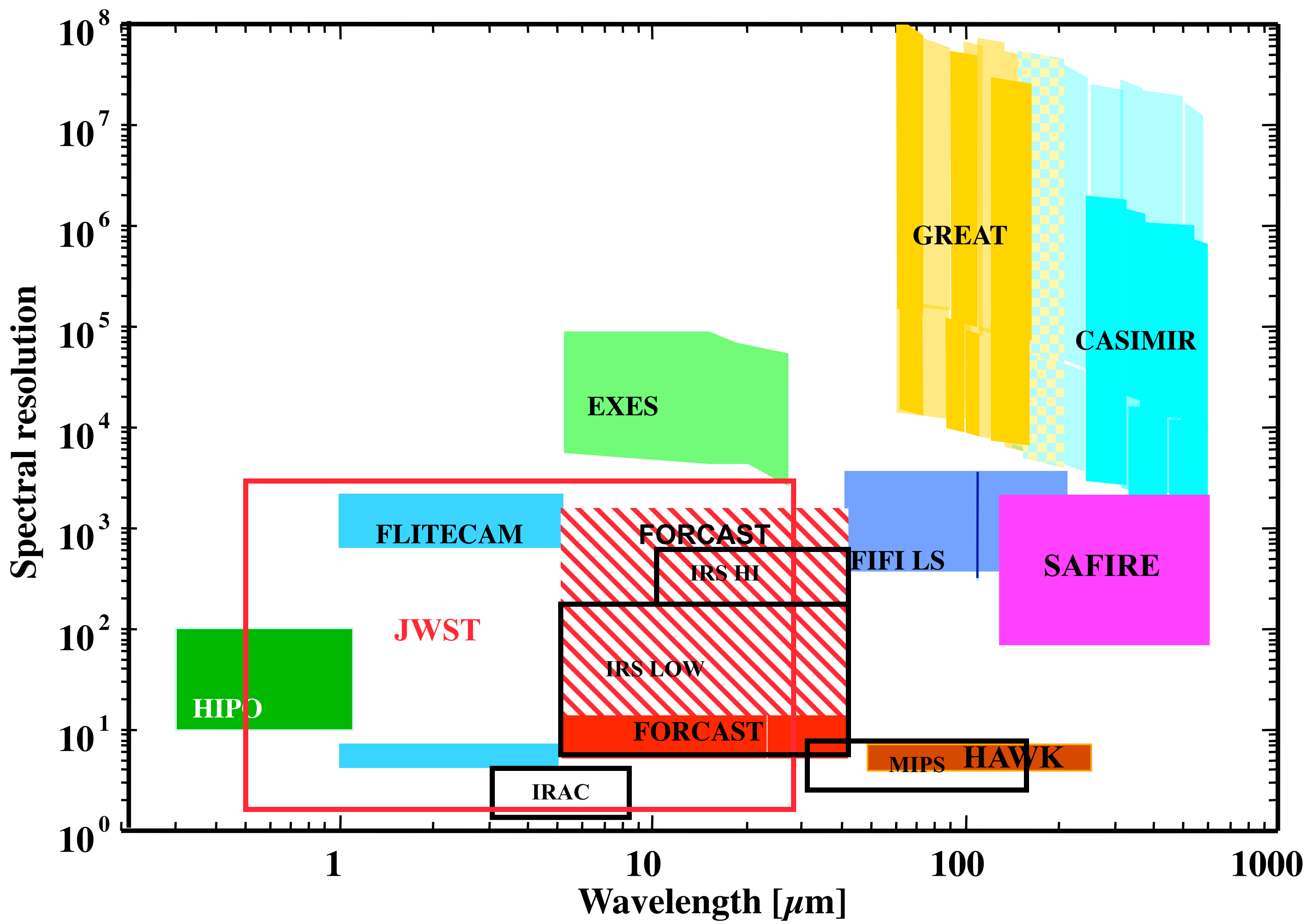
Working FORCAST instrument at Palomar in 2005



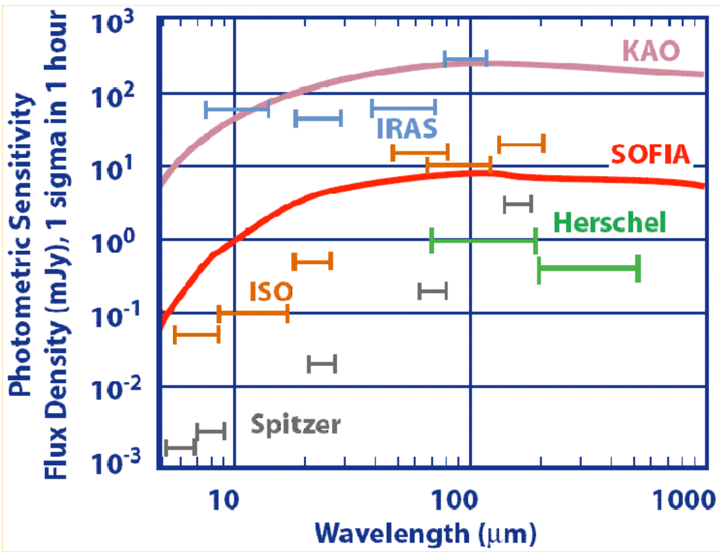
Lab-picture of GREAT equipped with the KOSMA 1.9THz channel

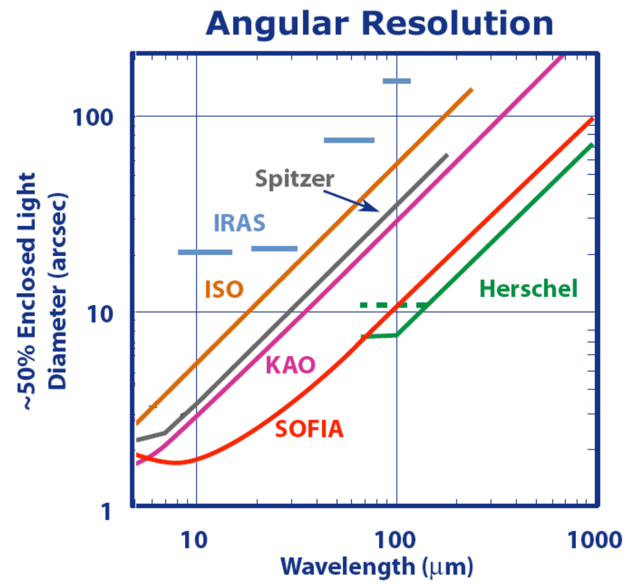
Successful lab demonstration of GREAT in July 2005

SOFIA First Generation Spectroscopy



Photometric Sensitivity and Angular resolution





SOFIA is as sensitive as ISO

SOFIA is diffraction limited beyond 25 μm (θmin ~ λ/10 in arcseconds) and can produce images three times sharper than those made by Spitzer

Line Sensitivities with Spectrometers
(4σ in 900 sec on source time)

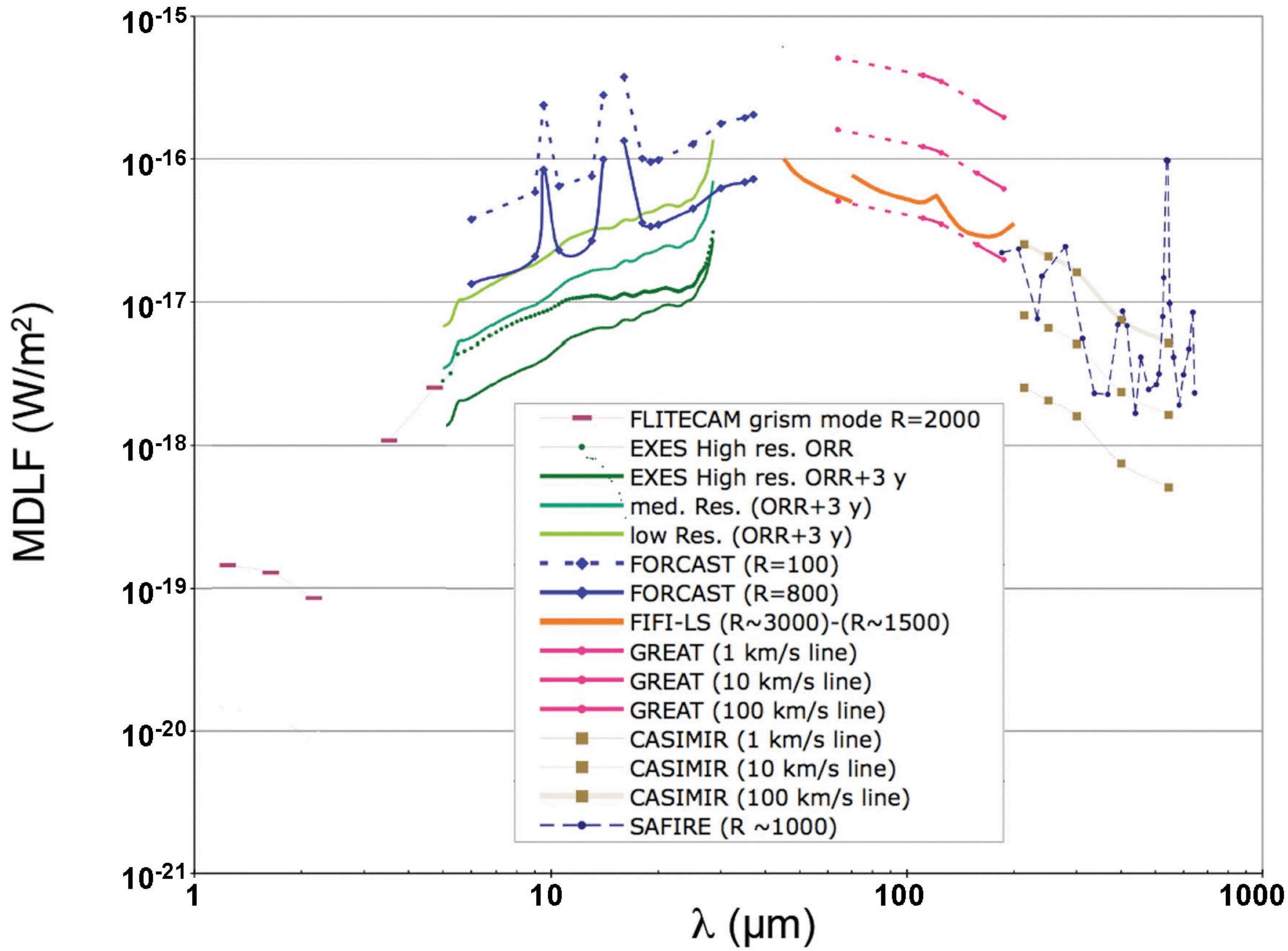


Table of Contents of "The Science Vision for the Stratospheric Observatory for Infrared Astronomy"

USRA NASA DLR SOFIA

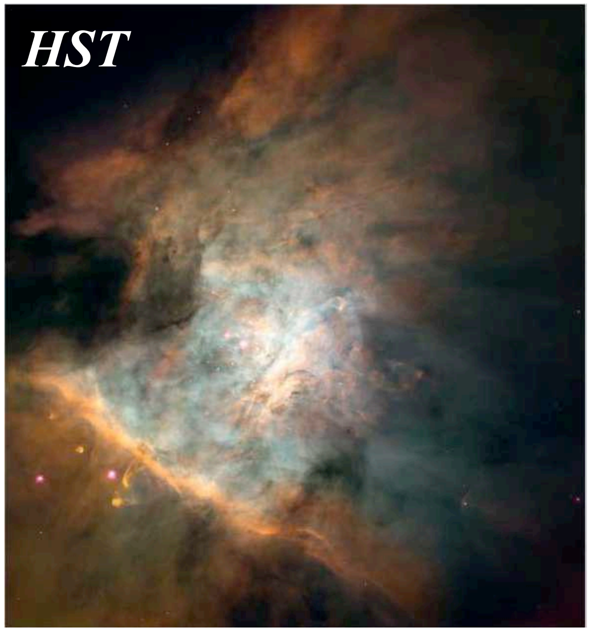
Key Astrophysics Questions for SOFIA

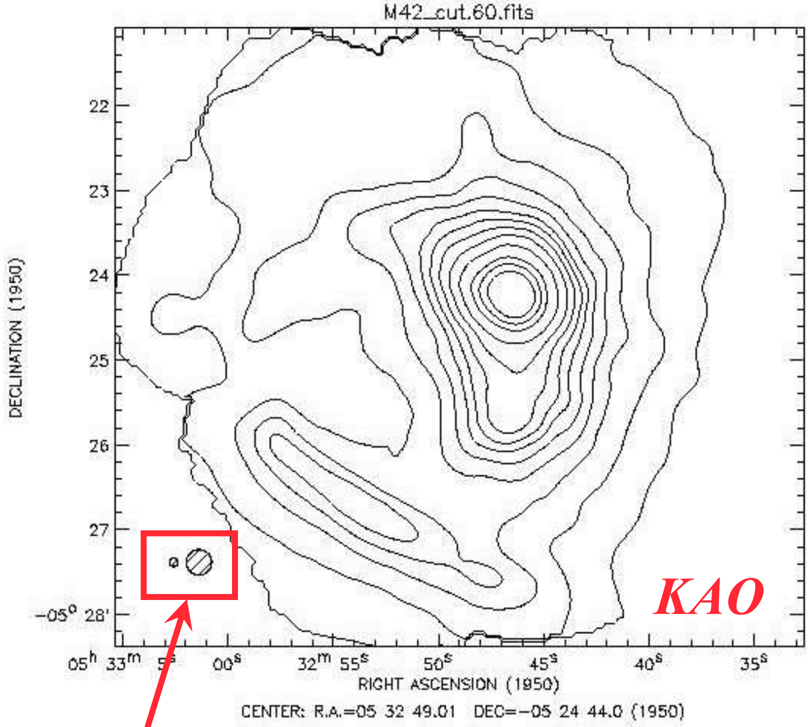
Chapter 2: The Formation of Stars and Planets

- *The Formation of Massive Stars*
- *Understanding Proto-planetary Disks*
- *Astrochemistry in Star Forming Regions*

SOFIA and Regions of Star Formation

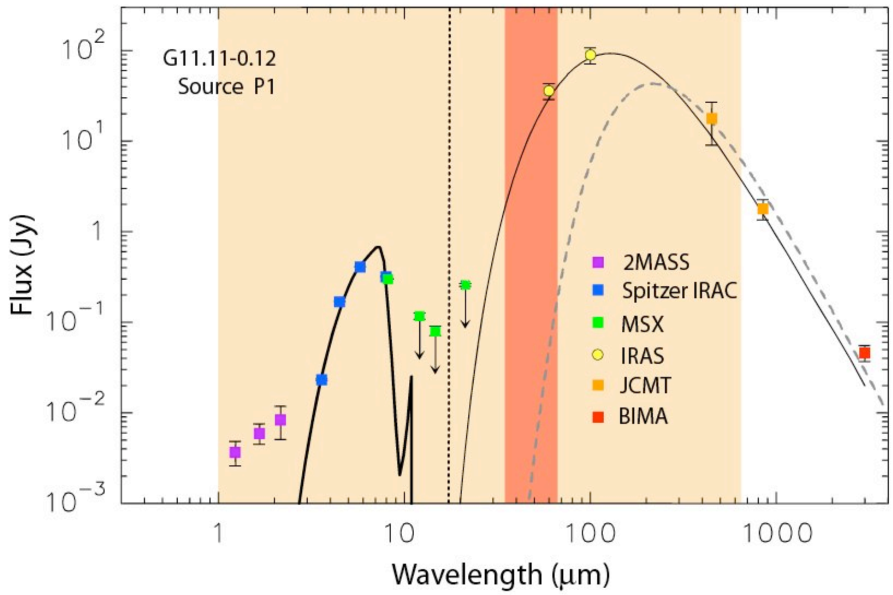
How will SOFIA shed light on the process of star formation in Giant Molecular Clouds like the Orion Nebula?



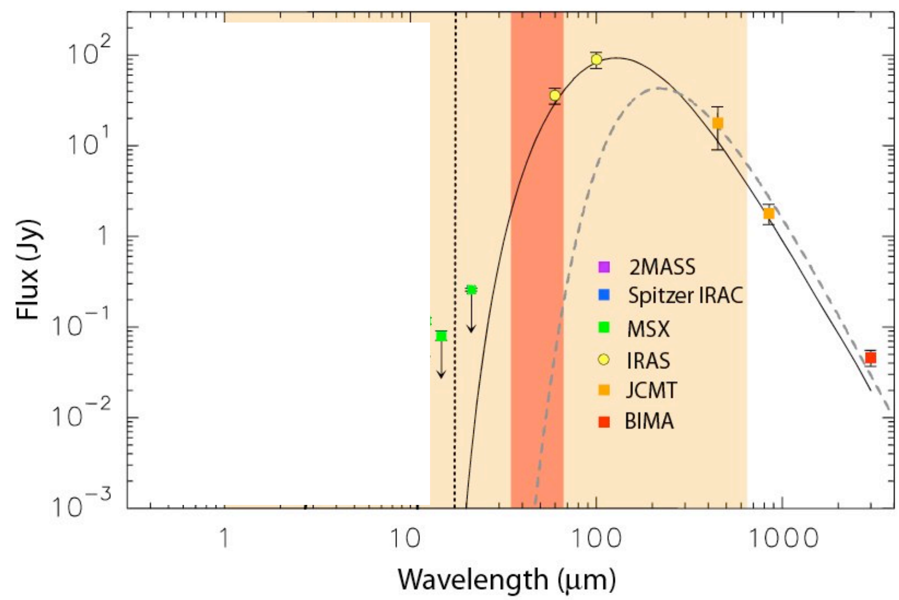


With 9 SOFIA beams for every 1 KAO beam, SOFIA imagers/HI-RES spectrometers can analyze the physics and chemistry of individual protostellar condensations where they emit most of their energy and can follow up on HERSCHEL discoveries.

Sources Embedded in Massive Cloud Cores

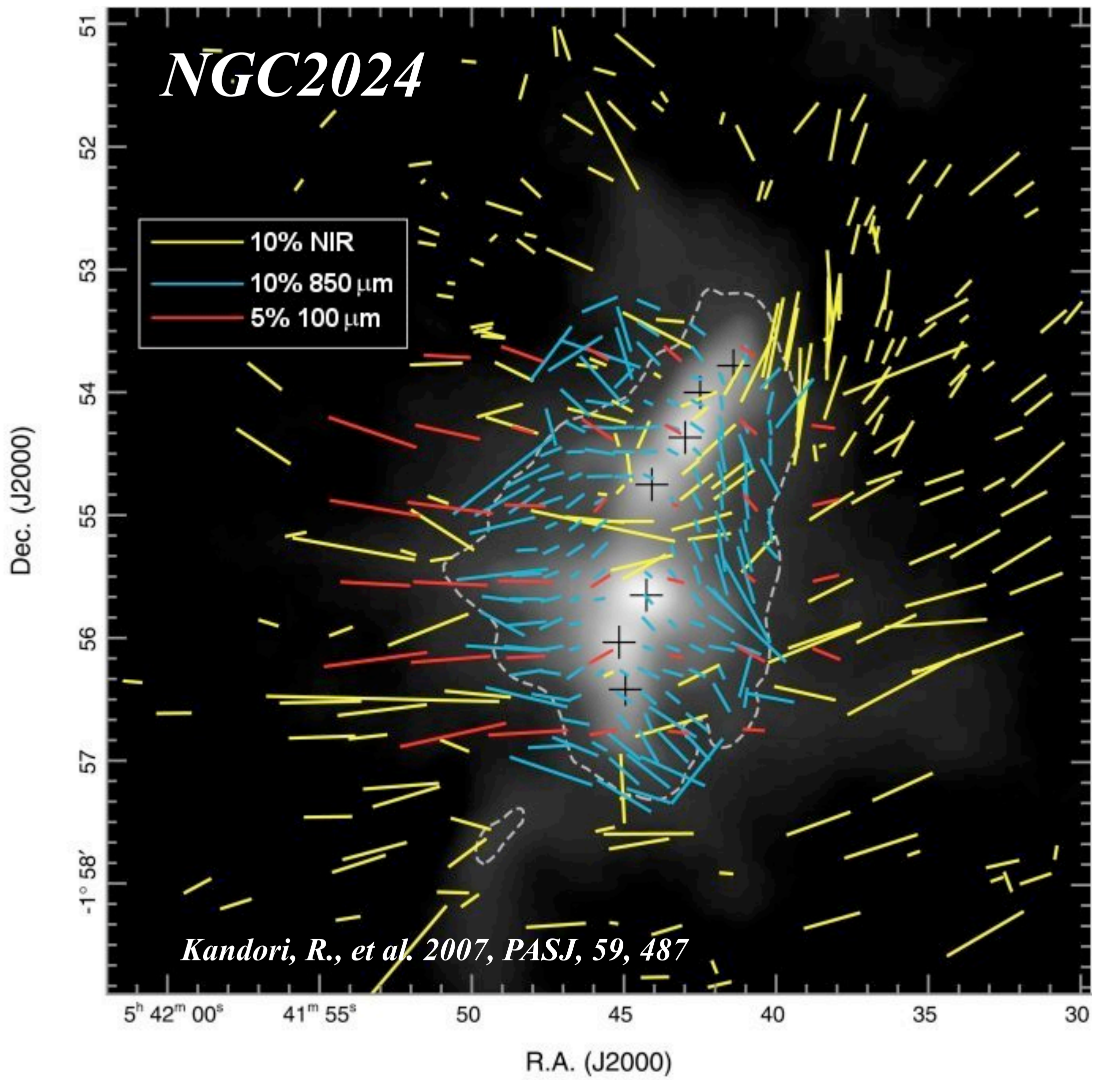


- ***In highly obscured objects, no mid-IR source may be detectable***



- ***20 to 100 microns can provide a key link to shorter wavelengths***

Magnetic Fields in Massive Star Forming Regions

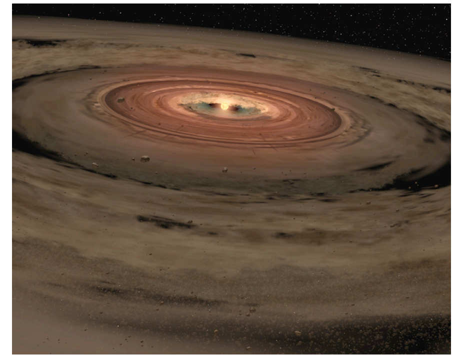


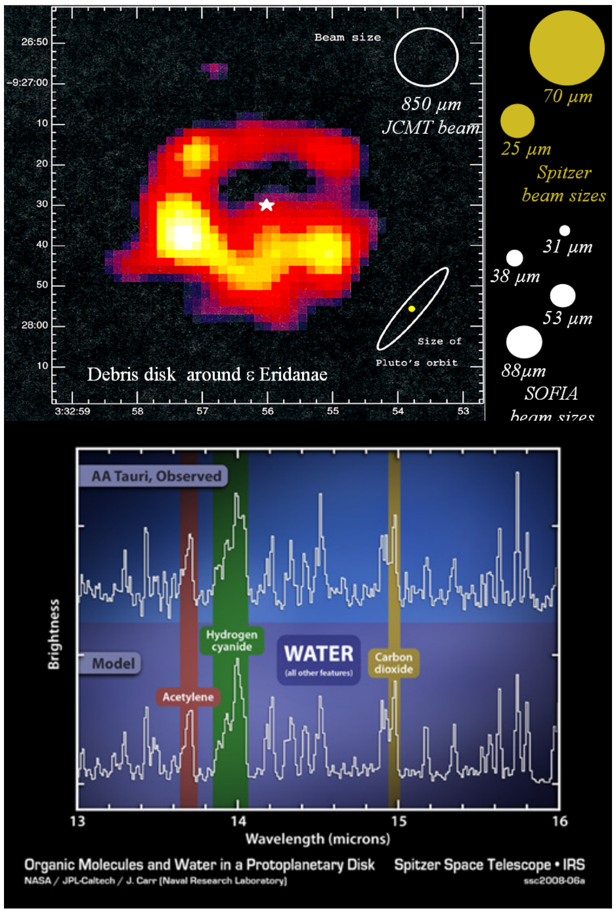
- *Within the dashed contour, NIR and sub-mm disagree on field direction. NIR probes outer low density material. FIR will probe warm, dense material*
- *A polarimetric capability for HAWC is being investigated*

IRSF/SIRIUS and JCMT/SCUBA data

SOFIA and Extra-Solar Circumstellar Disks

What can SOFIA tell us about circumstellar disks?

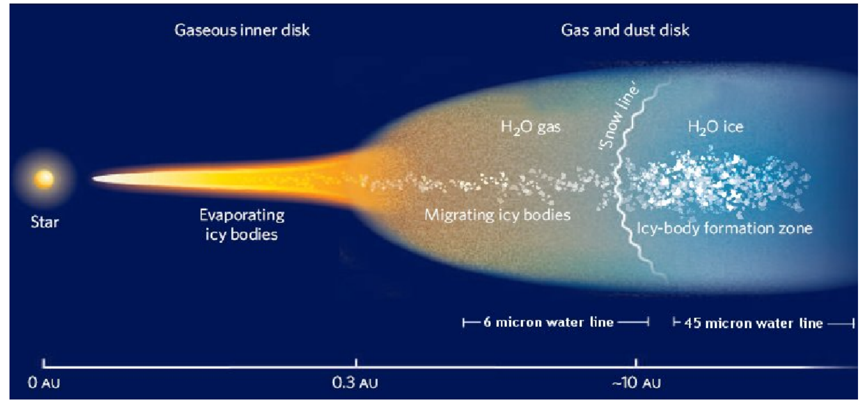




- *SOFIA imaging and spectroscopy can resolve disks to trace the evolution of the spatial distribution of the gaseous, solid, and icy gas and grain constituents*
- *SOFIA can shed light on the process of planet formation by studying the temporal evolution of debris disks*

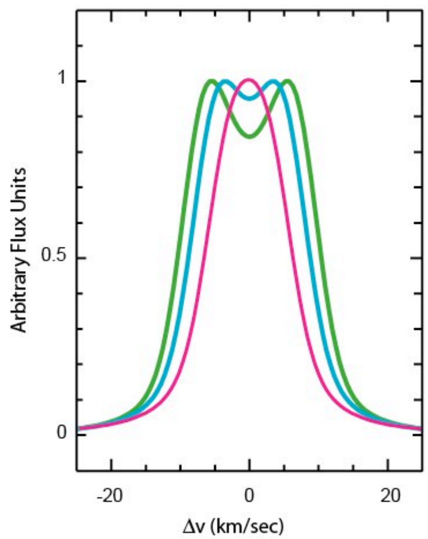
The chemistry of disks with radius and Age

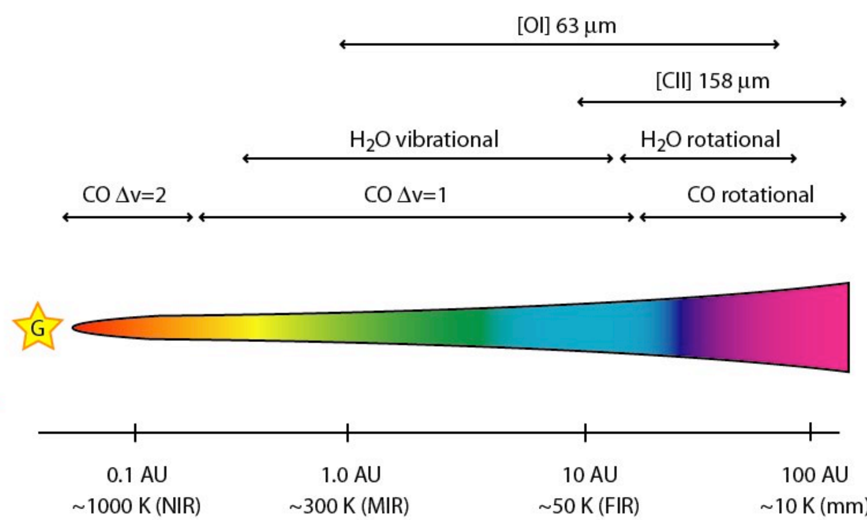
- *High spatial and spectral resolution can determine where different species reside in the disk*



- *small radii produce double-peaked, wider lines.*

- *Observing many disks at different ages will trace disk chemical evolution*





Astrochemistry in Star Forming Regions

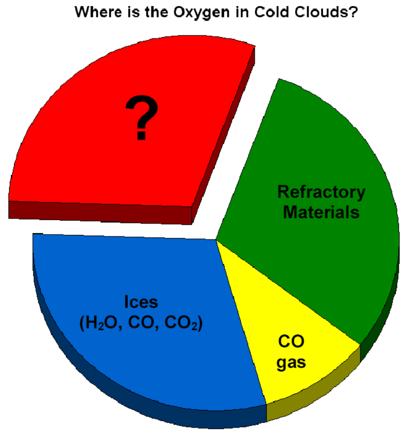
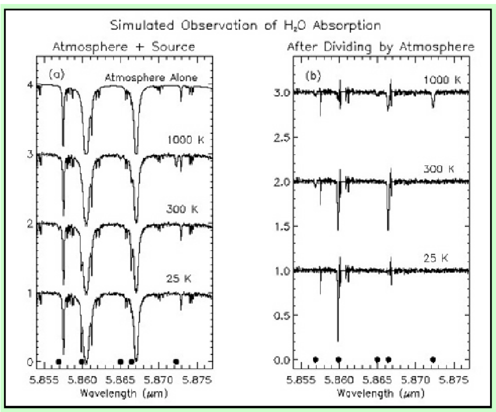


Figure 2-6. A pie chart showing the oxygen budget in cold clouds. Almost 1/3 of the oxygen is unaccounted for.



- *SOFIA is the only mission that can provide spectrally resolved data on the 63 and 145 μm [OI] lines to shed light on the oxygen deficit in circumstellar disks and star-forming clouds*

- *SOFIA has the unique ability to spectrally resolve water vapor lines in the Mid-IR to probe and quantify the creation of water in disks and star forming environments*

Key Astrophysics Questions for SOFIA

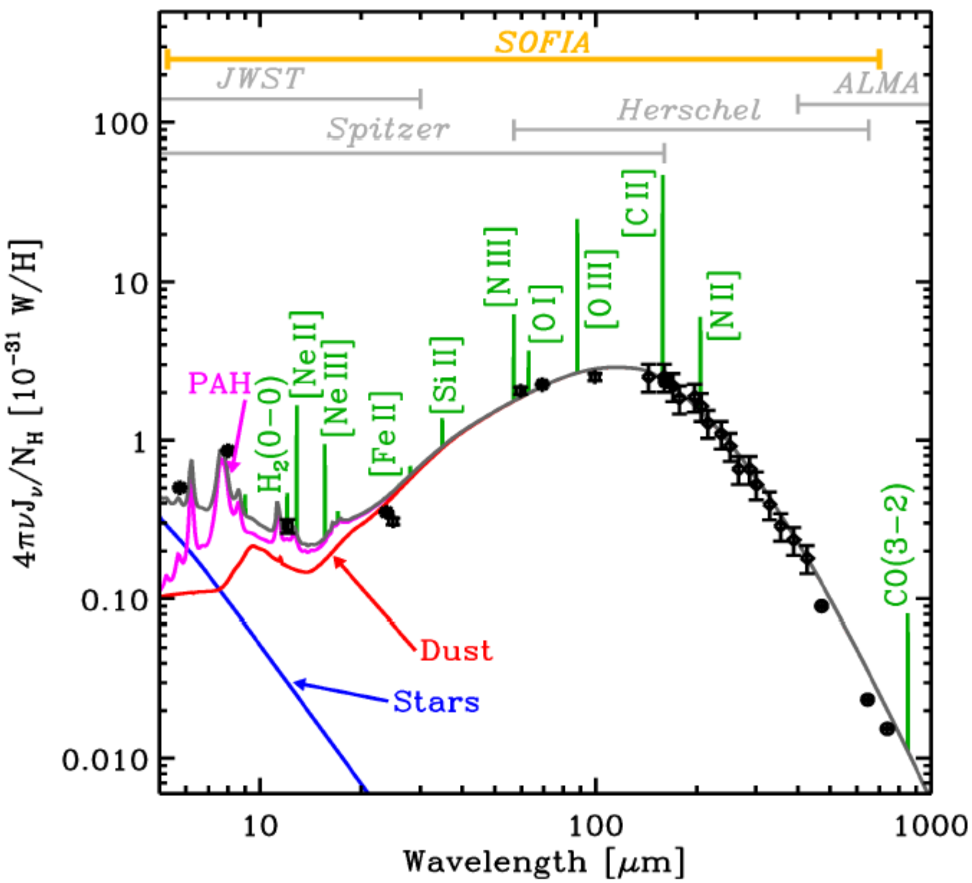
Chapter 3: The Interstellar Medium of the Milky Way

- Massive Stars and the ISM: Photodissociation Regions (PDRs)
- The Diversity and Origins of Dust in the ISM: Evolved Star Contributions
- The Role of Large, Complex Molecules in the ISM: Identification of PAHs
- Deuterium in the ISM: Constraints from HD

Related Objects of Opportunity

- Eruptive Variable Stars, Classical Novae, and Supernovae,

Thermal Emission from ISM Gas and Dust

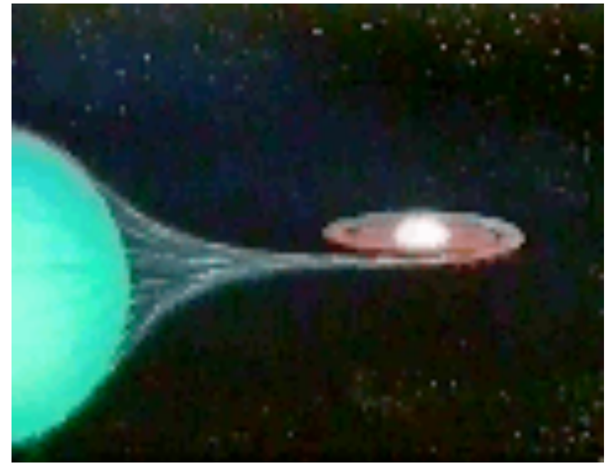


Spectral Energy Distribution (SED) of the entire LMC (courtesy of F. Galliano)

- ***SOFIA is the only mission in the next decade that is sensitive to the entire Far-IR SED of a galaxy that is dominated by emission from the ISM excited by radiation from massive stars and supernova shock waves***
- ***The SED is dominated by PAH emission, thermal emission from dust grains, and by the main cooling lines of the neutral and ionized ISM***

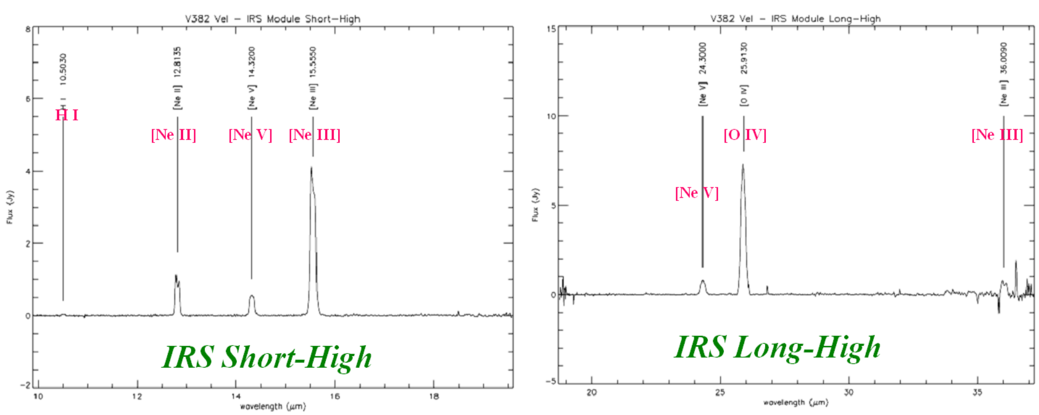
SOFIA and Classical Nova Explosions

What can SOFIA tell us about gas phase abundances in Classical Nova Explosions?



Spitzer Spectra of Nova V382 Vel

R. D. Gehrz, et al. 2005, ApJ, in preparation [PID 124]

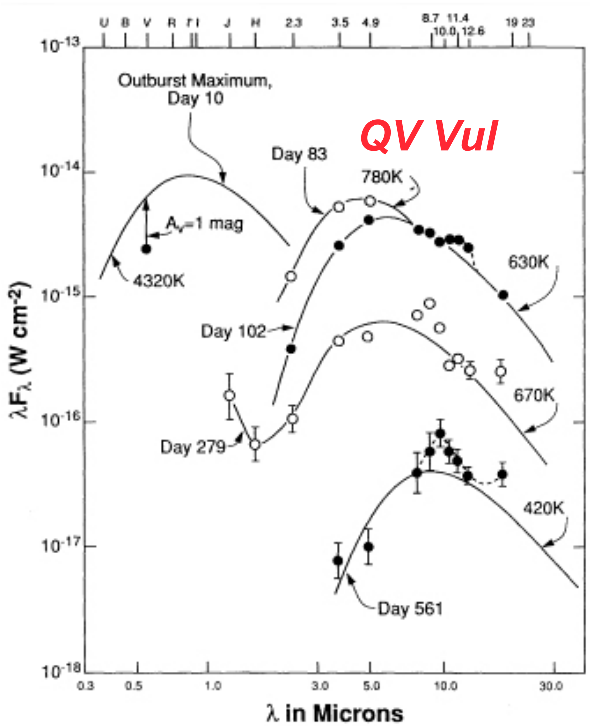


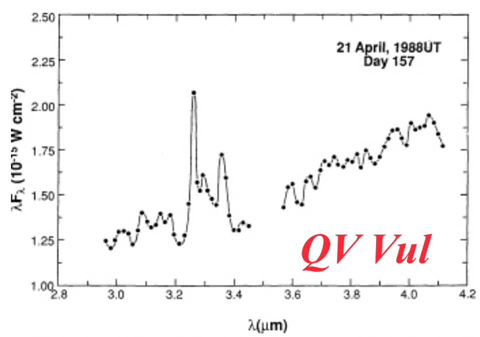
- *Gas phase abundances of CNOMgNeAl*
- *Contributions to ISM clouds and the primitive Solar System*
- *Kinematics of the Ejection*

SOFIA and Classical Nova Explosions

What can SOFIA tell us about the mineralogy of dust produced in Classical Nova Explosions?

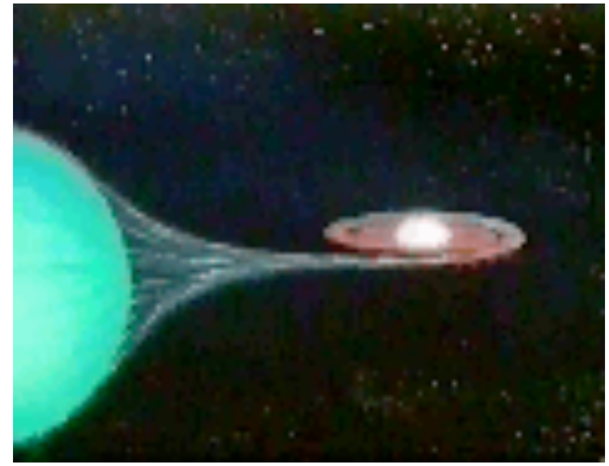
Gehrz et al. 1992 (Ap. J., 40, 671)





QV Vul formed four types of stardust:

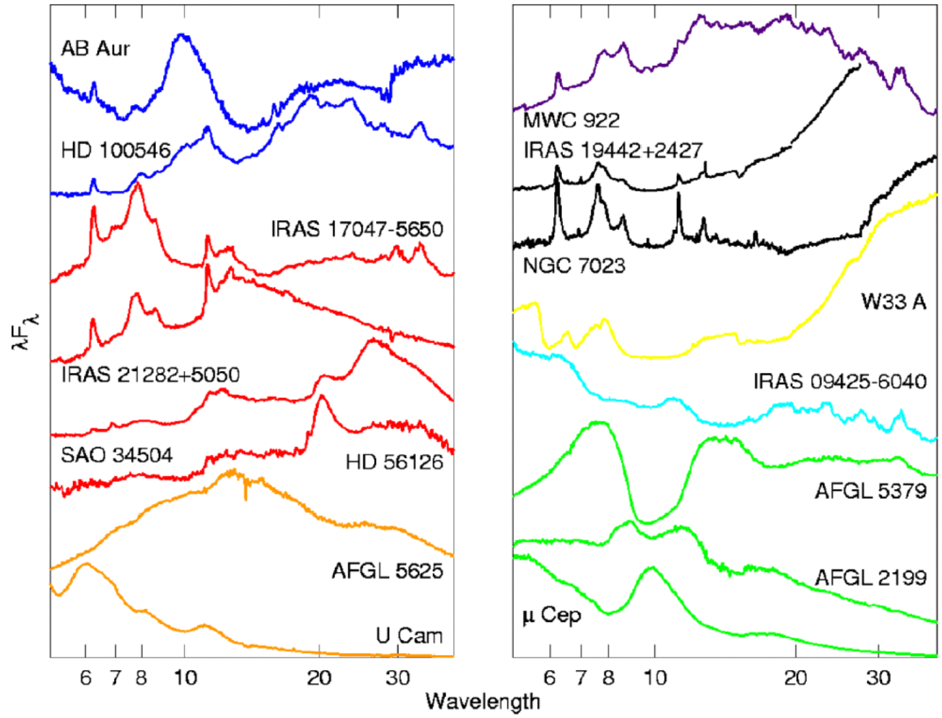
- *Amorphous carbon*
- *SiC*
- *Amorphous silicates*
- *Hydrocarbons*



- *Stardust formation, mineralogy, and abundances*
- *SOFIA's spectral resolution and wavelength coverage is required to study amorphous, crystalline, and hydrocarbon components*
- *Contributions to ISM clouds and the Primitive Solar System*

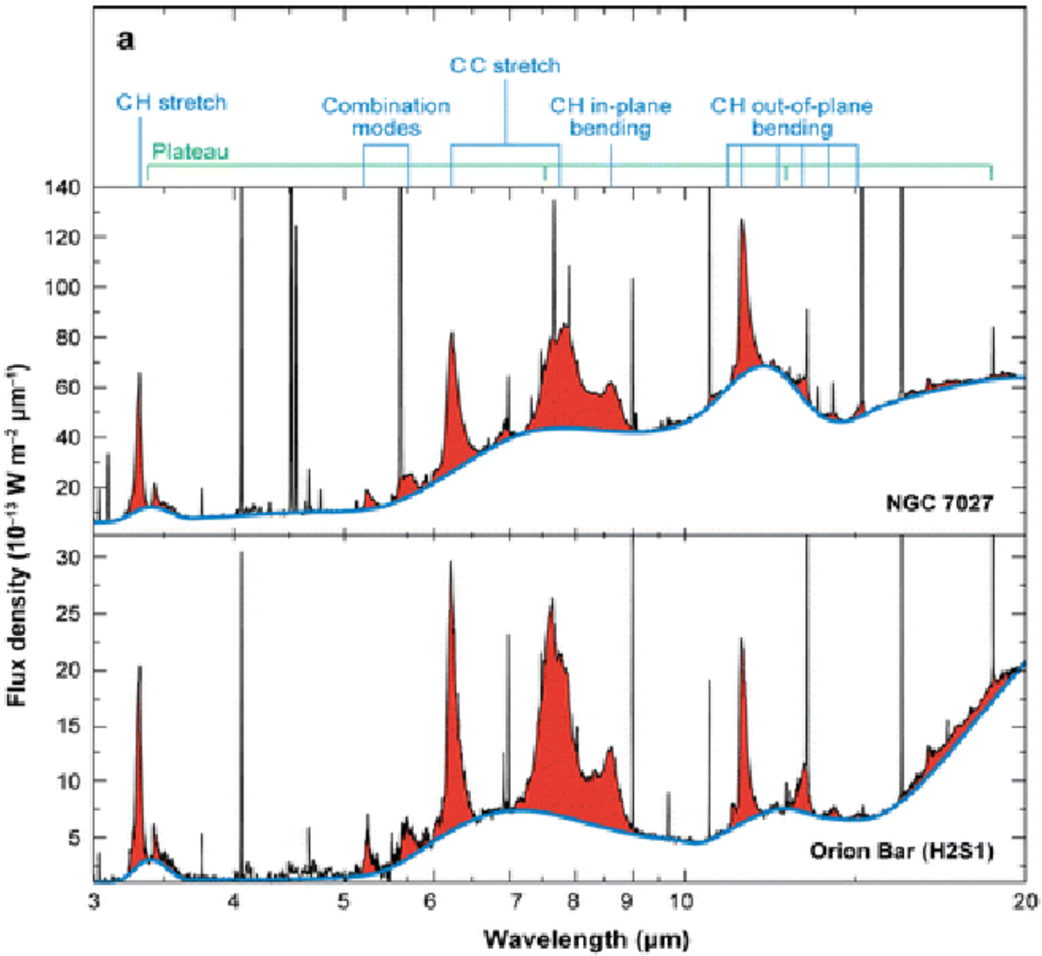
SOFIA Will Study the Diversity of Stardust

Herbig AeBe
Post-AGB and PNe
Mixed chemistry post-AGB
C-rich AGB
O-rich AGB
Mixed chemistry AGB
Deeply embedded YSO
HII region refection nebulae



- *ISO SWS Spectra: stardust is spectrally diverse in the regime covered by SOFIA*
- *Studies of stardust mineralogy*
- *Evaluation of stardust contributions from various stellar populations*
- *Implications for the lifecycle of gas and dust in galaxies*

Thermal Emission from PAH Rich Objects

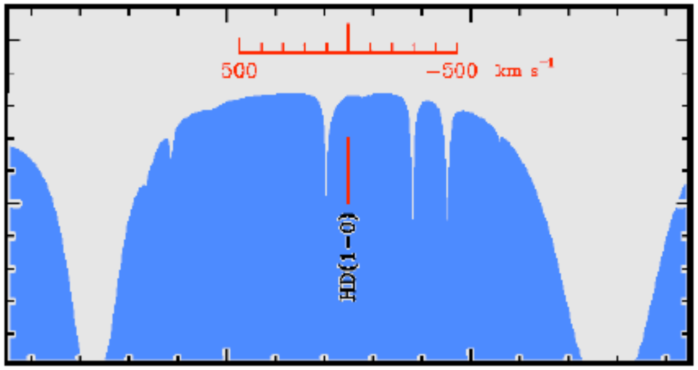


Vibrational modes of PAHs in a planetary nebula and the ISM (A. Tielens 2008)

- *A key question is whether portions of the aromatic population of PAHs are converted to species of biological significance*
- *Far-IR spectroscopy can constrain the size and shape of PAH molecules and clusters.*
- *The lowest lying vibrational modes ("drumhead" modes) will be observed by SOFIA's spectrometers*

SOFIA Observations of ISM HD

- The 112μm ground-state rotational line of HD is accessible to GREAT
- ISO detection of SGR B shows that HD column densities of ~ $10^{17} – 10^{18}$ cm^{-2} can be detected



Atmospheric transmission around the HD line at 40,000 feet

- All deuterium in the Universe was originally created in the Big Bang
- D is destroyed by astration in stars
- Therefore, D abundance probes the ISM that has never been cycled through stars
- 112 μm observations of HD can be used to determine ISM H/D abundances
- Cold HD (T<50K) is a proxy for cold molecular Hydrogen,
- The 112 μm line can be used to map the Galactic distribution of cold molecular gas just as 21 cm maps the distribution of neutral hydrogen

Key Astrophysics Questions for SOFIA

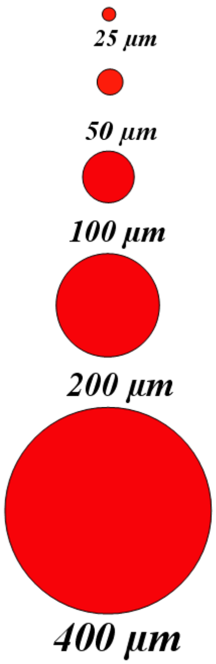
Chapter 4: Galaxies and the Galactic Center

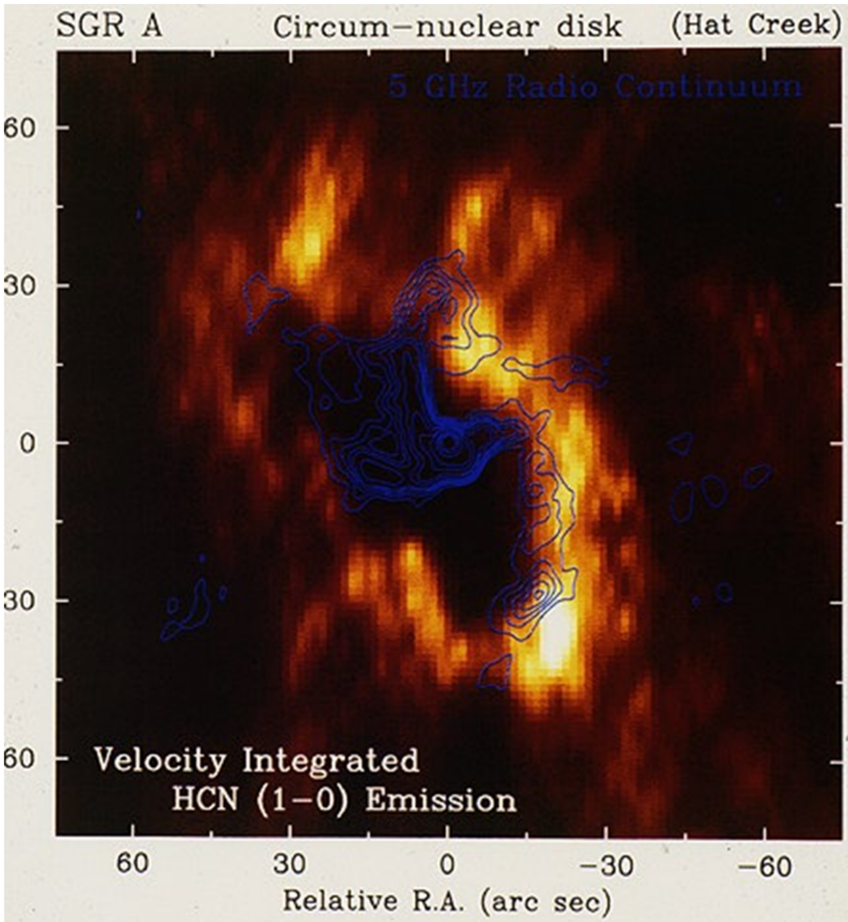
- ***The Galactic Center: Warm Clouds and Strong Magnetic Fields***

- ***The Interstellar Medium and the Star Formation History of External Galaxies***

- ***Tracing the Universe's Star Formation History with Far-IR Fine Structure Lines***

SOFIA and the Black Hole at the Galactic Center





SOFIA beams

- ***SOFIA imagers and spectrometers can resolve detailed structures in the circum-nuclear disk at the center of the Galaxy***
- ***An objective of SOFIA science is to understand the physical and dynamical properties of the material that feeds the massive black hole at the Galactic Center***

The ISM and Star Formation in External Galaxies

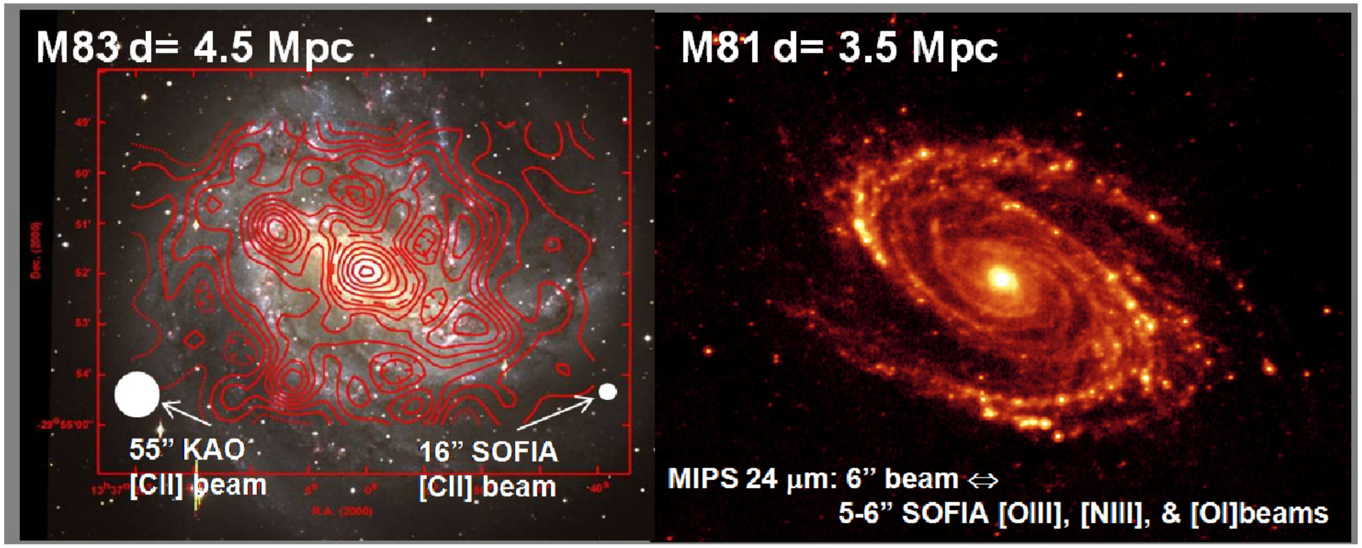
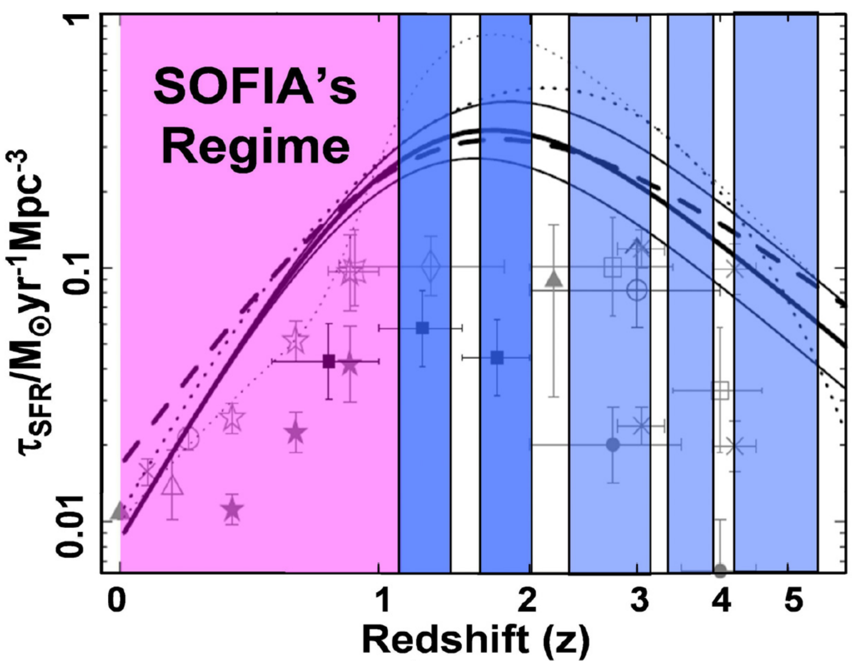


Figure 4-4. *(left) KAO [CII] map of M83 (d=4.5 Mpc) (contours, 55" beam) superposed on an optical image (Geis et al., in prep.). (right) MIPS 24 μm (6" beam) continuum image of M81 (d=3.5 Mpc). SOFIA can image nearby galaxies in the [OIII] 52 μm, [NIII] 57 μm, and [OI] 63 μm lines at a spatial resolution comparable to that of the Spitzer 24 μm image.*

- ***SOFIA observations of Far-IR lines can be conducted at unprecedented spatial resolution***

- ***ISM abundances and physical conditions can be studied as a function of location and nucleocentric distance***

The Star Formation History of the Universe



The co-moving history of star formation in the Universe (Smail et al. 2002) comparing SOFIA capabilities (pink) with existing data (symbols) and capabilities of ground-based observatories (blue).

- ***[CII] emission and the Far-IR continuum trace the physical extent and ages of starburst episodes with redshift***
- ***SOFIA can detect [CII] in the redshift range z = 0.25 to 1.25***
- ***This range covers most of cosmic history back to the time when the star formation rate per unit volume had peaked***
- ***SOFIA can determine whether starbursts at z = 1 were galaxy- wide or spatially confined***

Key Astrophysics Question for SOFIA

Chapter 5:Planetary Science

- Primitive Bodies
- Extra-Solar Planetary Material
- Giant Planets
- Venus: Earth's Neglected Sibling
- Titan: a Pre-biological Organic Laboratory

Related Objects of Opportunity

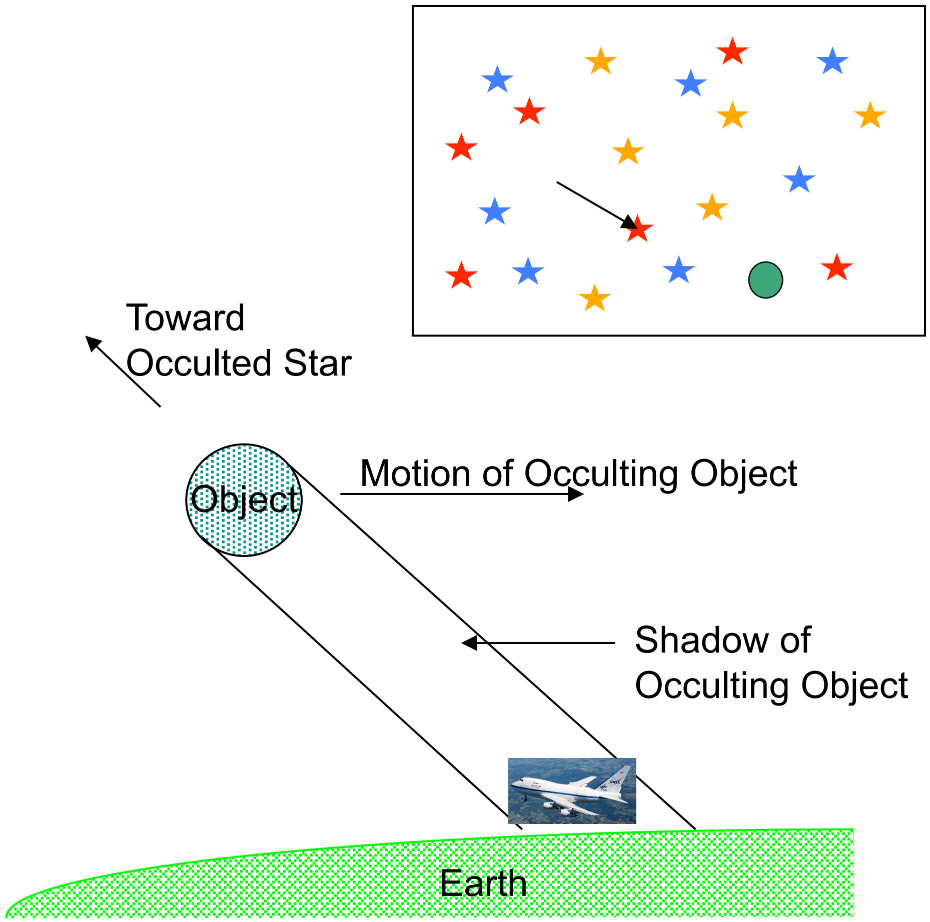
- Bright Comets, Occultations, Transits of Extra-Solar Planets

Occultation Astronomy with SOFIA

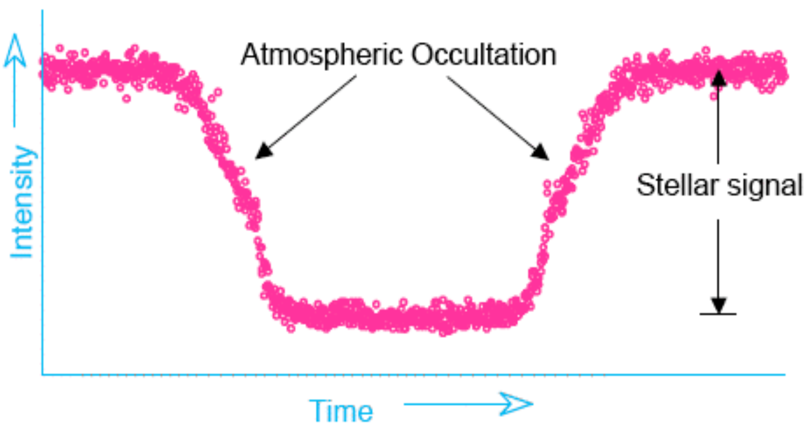
How will SOFIA help determine the properties of small Solar System bodies?

- ***Occultation studies probe sizes, atmospheres, satellites, and rings of small bodies in the outer Solar system.***

- ***SOFIA can fly anywhere on Earth to position itself in the occultation shadow. Hundreds of events are available per year compared to a handful for fixed ground and space-base observatories.***

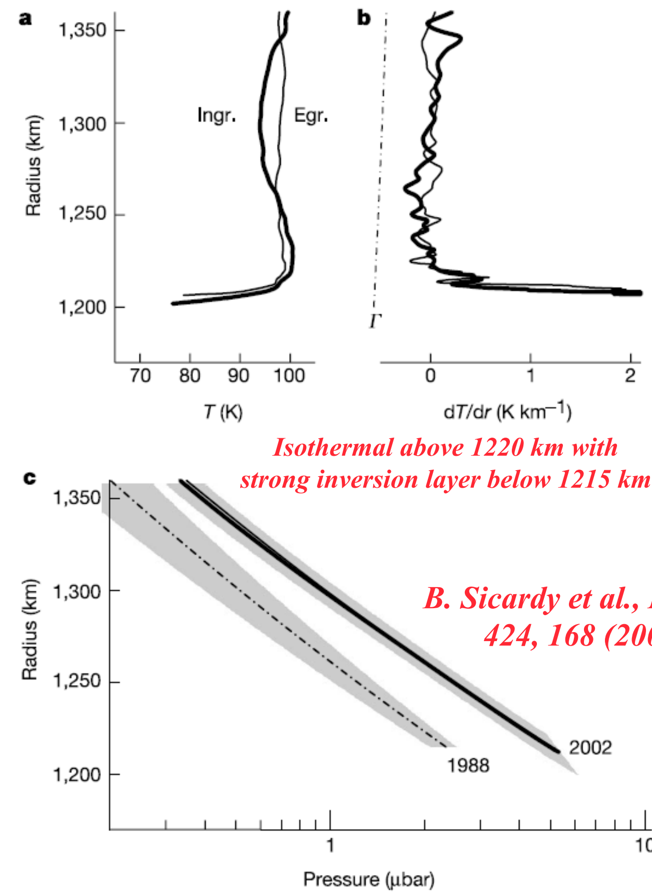


Occultations and Atmospheres



This occultation light curve observed on the KAO (1988) probed Pluto's atmosphere

J. L. Elliot et al., Icarus 77, 148-170 (1989)

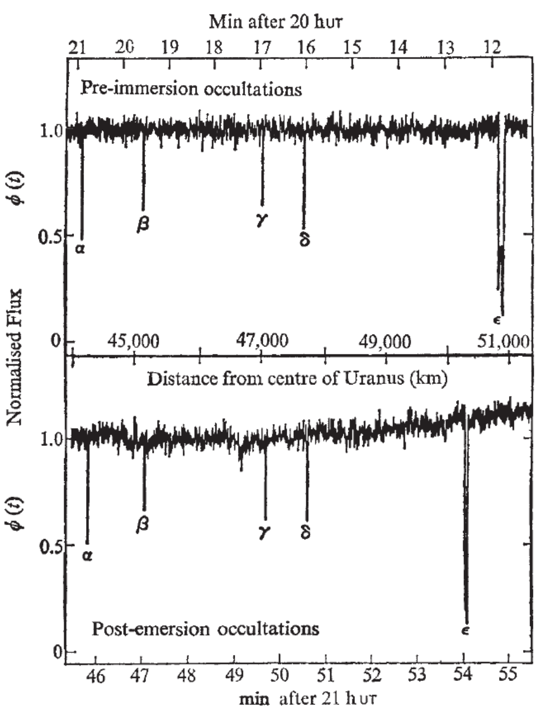


Isothermal above 1220 km with strong inversion layer below 1215 km

B. Sicardy et al., Nature, 424, 168 (2003)

Figure 2 Temperature and pressure profiles of Pluto's atmosphere derived from the inversion of the P131.1 light curve. This inversion[17] assumes a spherically symmetric and transparent atmosphere. It first provides the atmospheric refractivity profile, then the density profile for a given gas composition, and finally the temperature profile, assuming an ideal gas in hydrostatic equilibrium. We assume for Pluto a pure molecular nitrogen[6] atmosphere,

Occultations: Rings and Moons



Uranus' Rings: The Story of a Discovery

— Sun Photo by Liz Warner

THE TEAM: Researchers Edward Dunham (l.), James Elliot, and Douglas Mink examine the unexpected signal pattern produced on the charter recorder by the outermost ring of Uranus.

This occultation light curve observed on the KAO in 1977 shows the discovery of a five ring system around Uranus

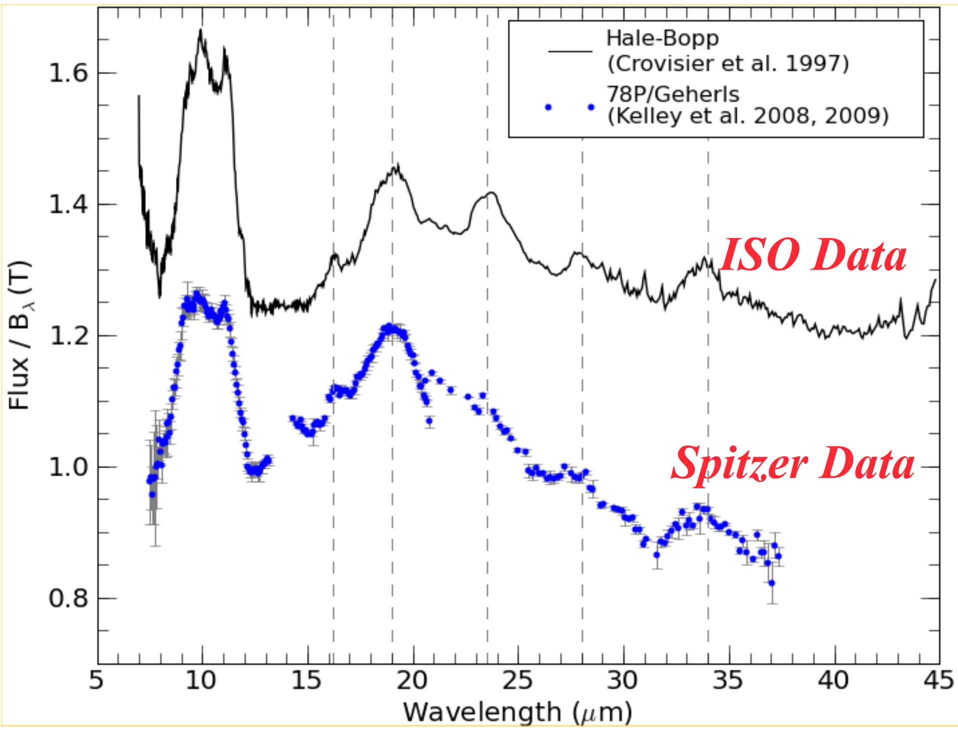
J. L. Elliot, E. Dunham, and D. Mink, Nature 267, 328-330 (1977)

Observing Comets with SOFIA

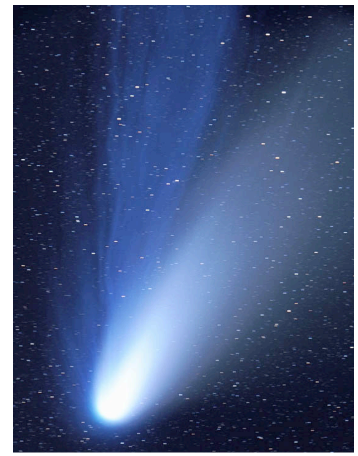
- Comet nuclei are the Rosetta Stone of the Solar System and their ejecta reveal the contents and physical conditions of the primitive Solar Nebula when they are ablated during perihelion passage
- Comet nuclei, comae, tails, and trails emit primarily at the thermal IR wavelengths accessible with SOFIA
- Emission features from grains, ices, and molecular gases occur in the IR and are strongest when comets are near perihelion
- SOFIA has unique advantages: IR Space platforms like Spitzer, Herschel, and JWST) cannot view comets during perihelion passage due to pointing constraints

SOFIA and Comets: Mineral Grains

What can SOFIA observations of comets tell us about the origin of the Solar System?



The vertical lines mark features of crystalline Mg-rich crystalline olivine (forsterite)

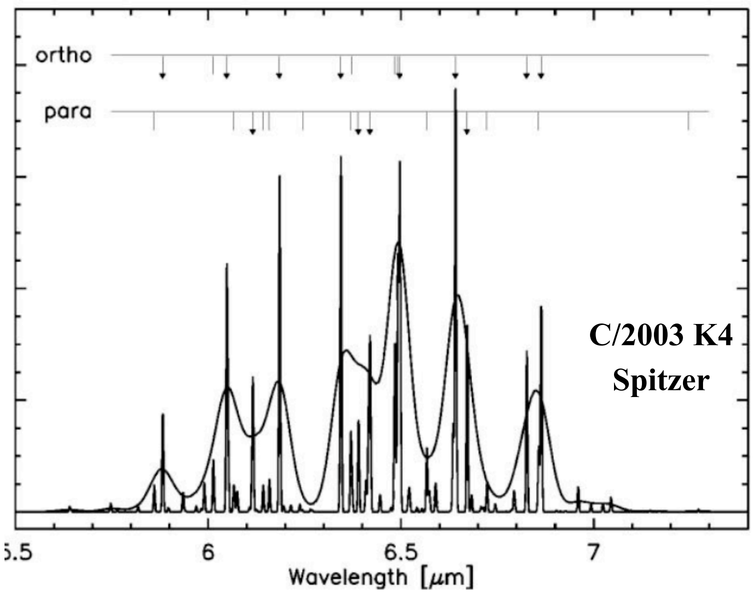


- *Comet dust mineralogy: amorphous, crystalline, and organic constituents*
- *Comparisons with IDPs and meteorites*
- *Comparisons with Stardust*
- *Only SOFIA can make these observations near perihelion*

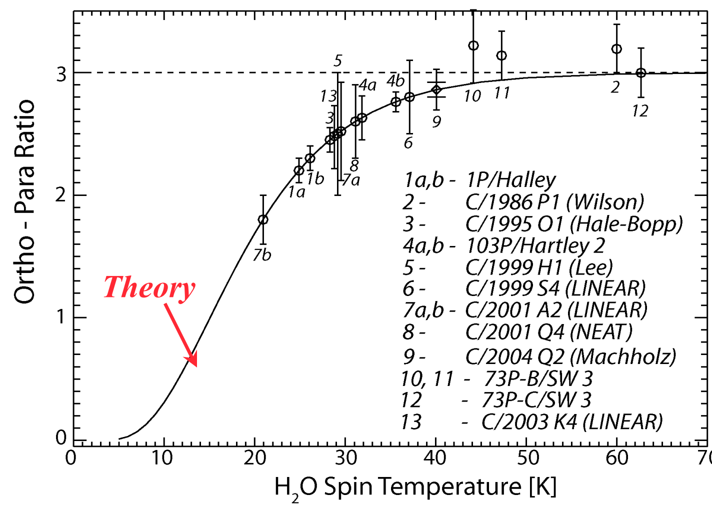
SOFIA and Comets: Gas Phase Constituents

What can SOFIA observations of comets tell us about the origin of the Solar System?

C. E. Woodward et al. 2007, ApJ, 671, 1065



B. P. Bonev et al. 2007, ApJ, 661, L97



- ***Production rates of water and other volatiles***
- ***Water H_2 ortho/para (parallel/antiparallel) hydrogen spin isomer ratio gives the water formation temperature; a similar analysis can done on ortho/para/meta spin isomers of CH_4***
- ***Only SOFIA can make these observations near perihelion***

SOFIA and Comets: Protoplanetary Disks

What can SOFIA observations of comets tell us about the origins of our Solar System and other solar systems?

ISO Observations — Adapted from Crovisier et al. 1996, Science 275, 1904 and Malfait et al. 1998, A&A 332, 25

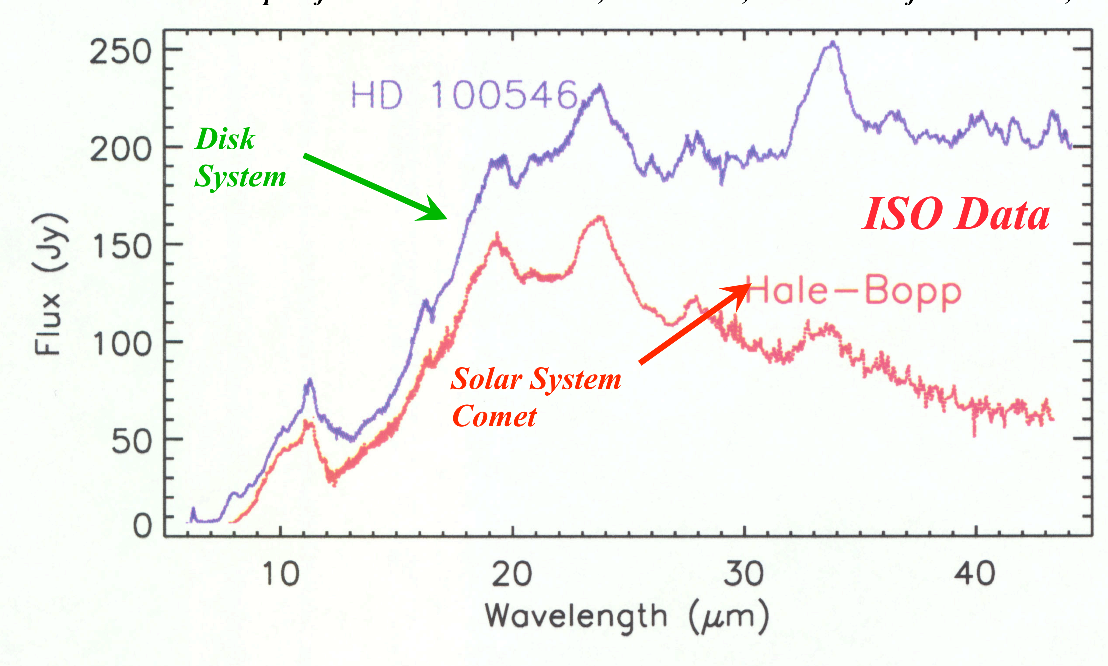
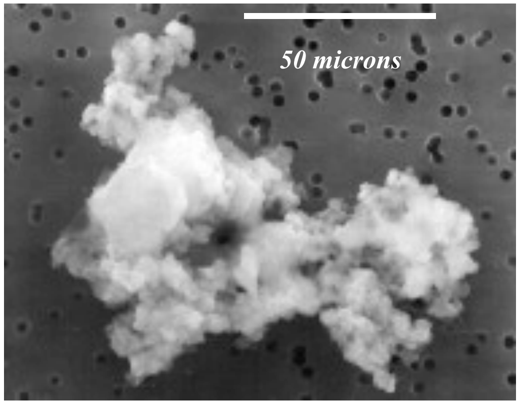


Image of Solar System IDP (Interplanetary Dust Particle)



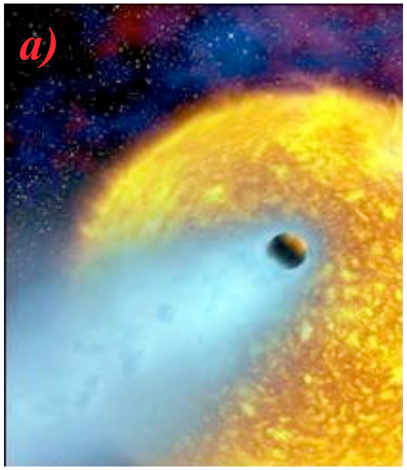
- *The similarities in the silicate emission features in HD 100546 and C/1995 O1 Hale-Bopp suggest that the grains in the stellar disk system and the small grains released from the comet nucleus were processed in similar ways*

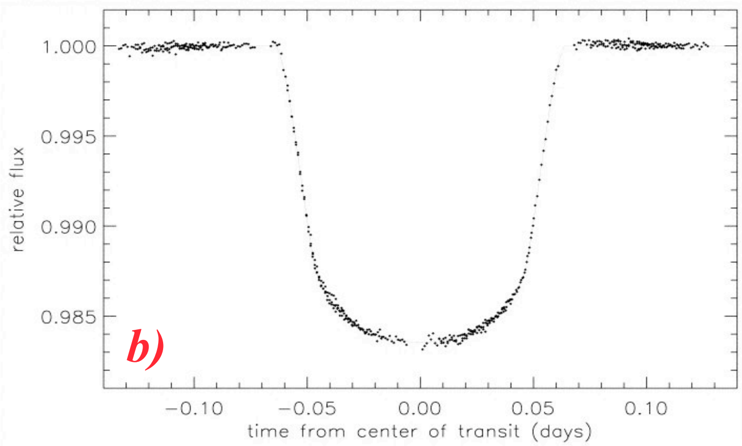
USRA NASA DLR SOFIA

SOFIA and Extra-solar Planet Transits

How will SOFIA help us learn about the properties of extra-solar planets?

- *More than 268 extra-solar planets; more than 21 transit their primary star*
- *SOFIA flies above the scintillating component of the atmosphere where it can detect transits of planets across bright stars at high signal to noise*





HD 209458b transit:

a) artist's concept and

b) HST STIS data

- *Transits provide good estimates for the mass, size and density of the planet*
- *Transits may reveal the presence of, satellites, and/or planetary rings*

Early General Observer Opportunities

- *Open Door Flights will begin at Palmdale in late 2009*
- *First light images will be obtained during winter 2009/2010*
- *Early Short Science in 2010 with FORCAST (US 5-40 µm imager and GREAT (German heterodyne 60 to 200 µm Spectrometer)*
  - *Proposals are in and teams have been selected*
  - *Very limited number of flights (~3)*
  - *GO's will not fly*
- *Early Basic Science for GOs in 2010 with FORCAST and GREAT*
  - *Draft call was released in Jan 2009*
  - *Final call to be released in December 2009*
  - *Longer period (~15 Flights)*
- *General Observer (GO) Science: First Call for proposals in late 2010*
  - *~20 flights per year until full science operations begin in 2014*

SOFIA Instrumentation Development Program

- ***The next call for instruments will be at First Science ~ FY '10***
- ***The instrumentation development program will include:***
  - ***New science instruments, both FSI and PSI***
  - ***Studies of instruments and technology***
  - ***Upgrades to present instruments***
- ***There will be additional calls every 3 years***
- ***There will be one new instrument or upgrade per year***
- ***Funding for new instruments and technology is ~$10 M/yr***

Summary

- *The Program is making progress!*
  - *Aircraft structural modifications complete*
  - *Telescope installed, several instruments tested on ground observatories*
  - *Full envelope closed door flight testing is complete.*
  - *Door motor drive, coated primary mirror were installed during summer of 2008*
  - *First light will be in early 2009*
- *SOFIA will be one of the primary observational facilities for far-IR and submillimeter astronomy for many years*

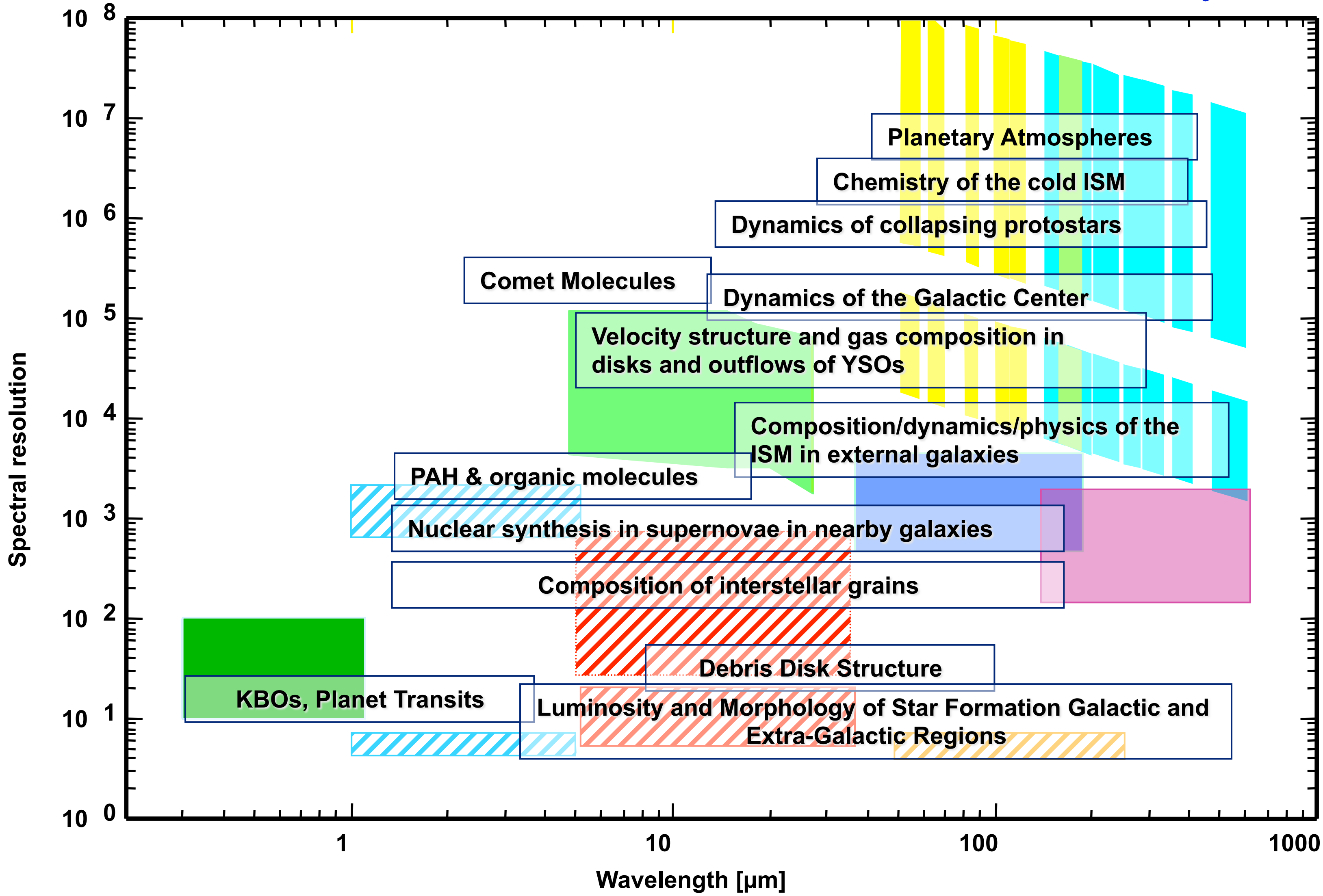
http://www.sofia.usra.edu/

Backup

The Initial SOFIA Instrument Complement

- *HIPO: High-speed Imaging Photometer for Occultation*
- *FLITECAM: First Light Infrared Test Experiment CAMera*
- *FORCAST: Faint Object InfraRed CAmera for the SOFIA Telescope*
- *GREAT: German Receiver for Astronomy at Terahetz Frequencies*
- *CASIMIR: CAltech Submillimeter Interstellar Medium Investigations Receiver*
- *FIFI-LS: Field Imaging Far-Infrared Line Spectrometer*
- *HAWC: High-resolution Airborne Wideband Camera*
- *EXES: Echelon-Cross -Echelle Spectrograph*
- *SAFIRE: Submillimeter And Far InfraRed Experiment*

SOFIA: Science For the Whole Community



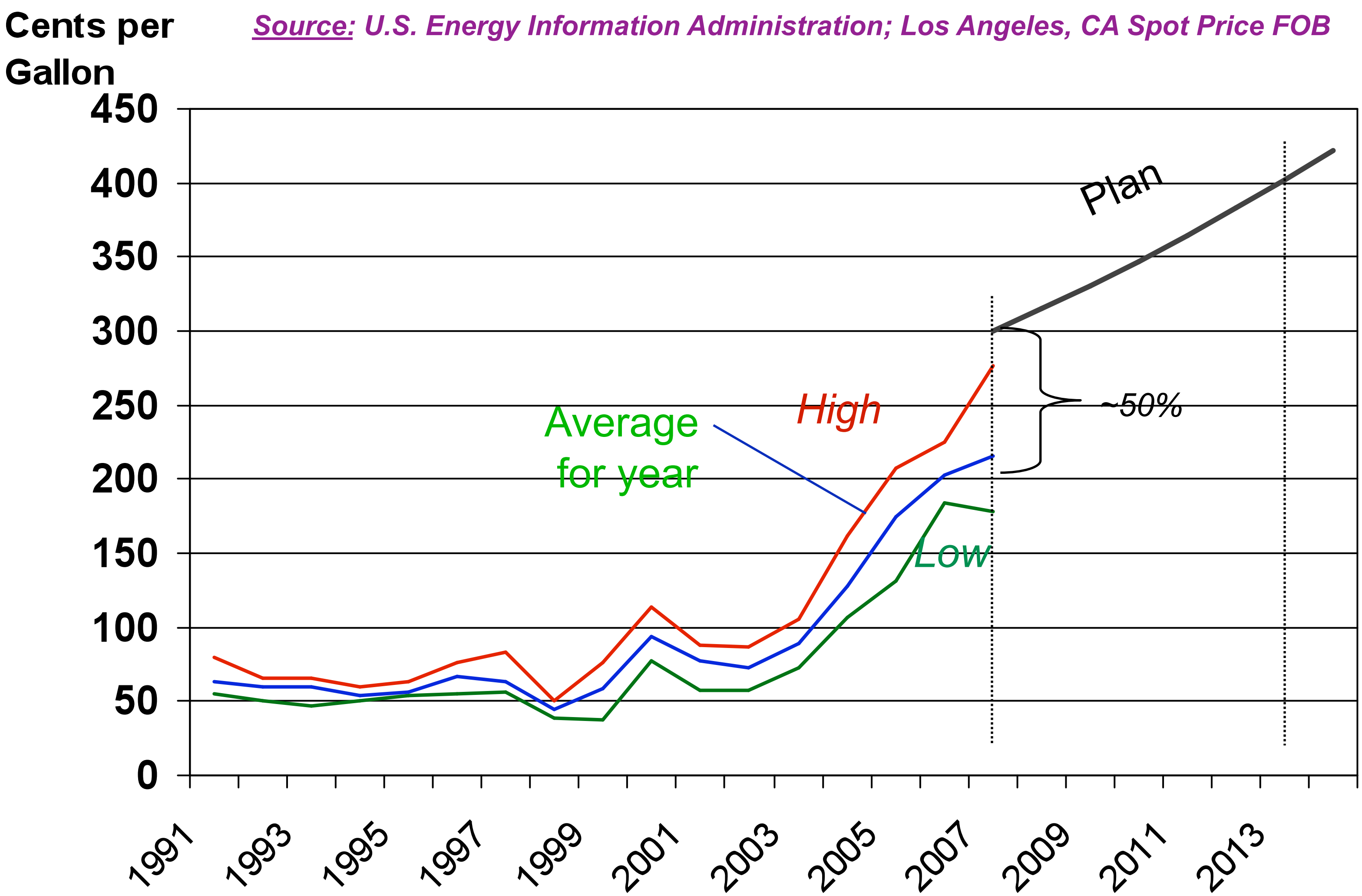
Annual Fuel Costs for Full SOFIA Operations

- ***The total annual fuel cost computed at a spot fuel price of $3.99/ gal (7/1/08) and 1040 total flight hours is $14.65M, of which the DLR pays $2.93M***

- ***The US fuel cost of $11.72M is approximately 15% of the total US SOFIA annual operating budget***

- ***The US annual operating budget includes reserves of 10%, so that a fuel price increase of 50% would reduce the available reserves to 2% of the annual US operating budget***

Jet Fuel Price History

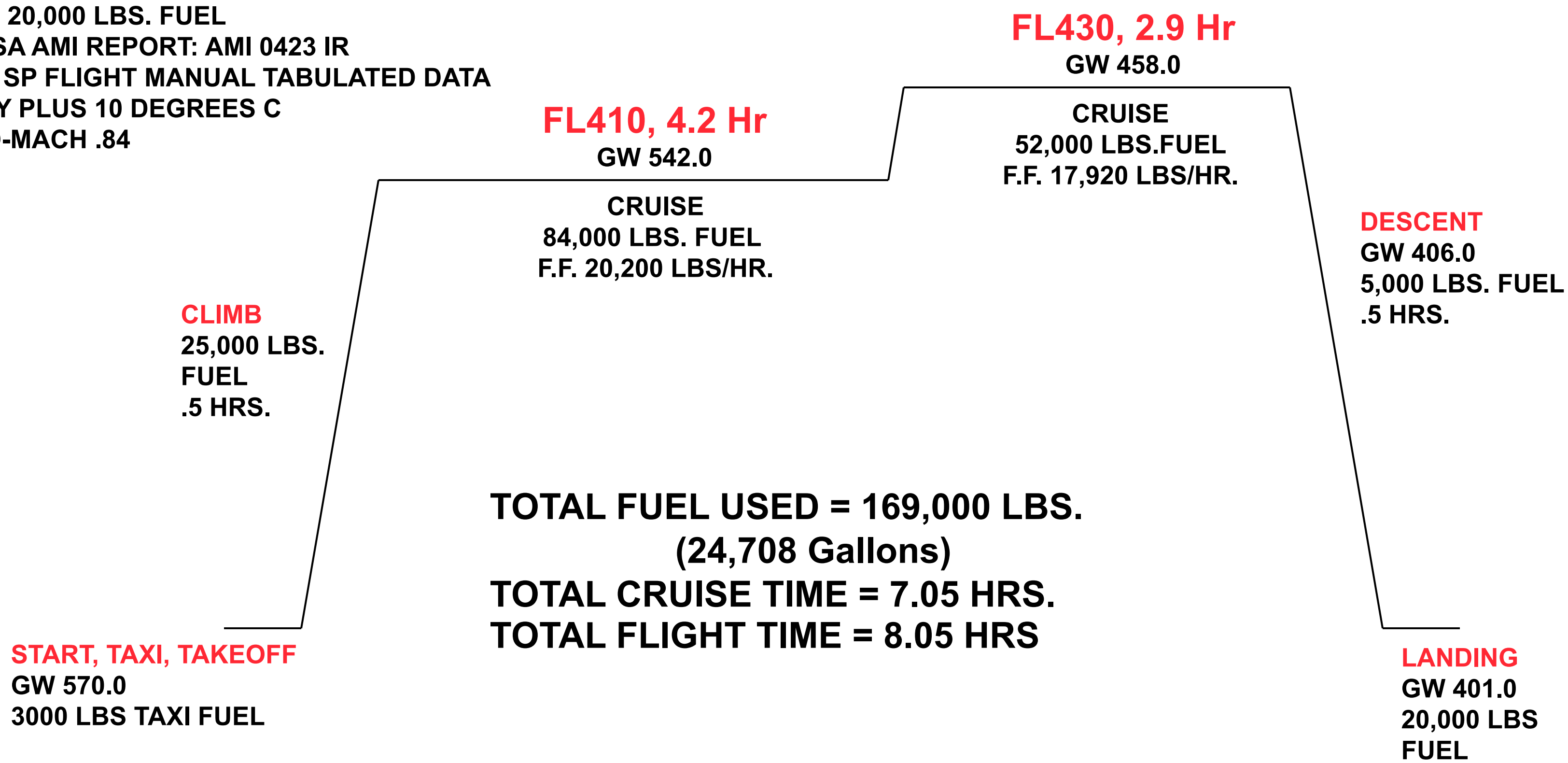


Flight Profile 1

Performance with P&W JT9D-7J Engines: Observations - start FL410, duration 7.1 Hr

ASSUMPTIONS

ZFW 381,000 LBS.
ENGINES OPERATE AT 95% MAX CONT THRUST AT CRUISE
25,000 LBS. FUEL TO FIRST LEVEL OFF
CLIMB TO FIRST LEVEL-OFF AT MAX CRUISE WT
LANDING WITH 20,000 LBS. FUEL
BASED ON NASA AMI REPORT: AMI 0423 IR
BASED ON 747 SP FLIGHT MANUAL TABULATED DATA
STANDARD DAY PLUS 10 DEGREES C
CRUISE SPEED-MACH .84



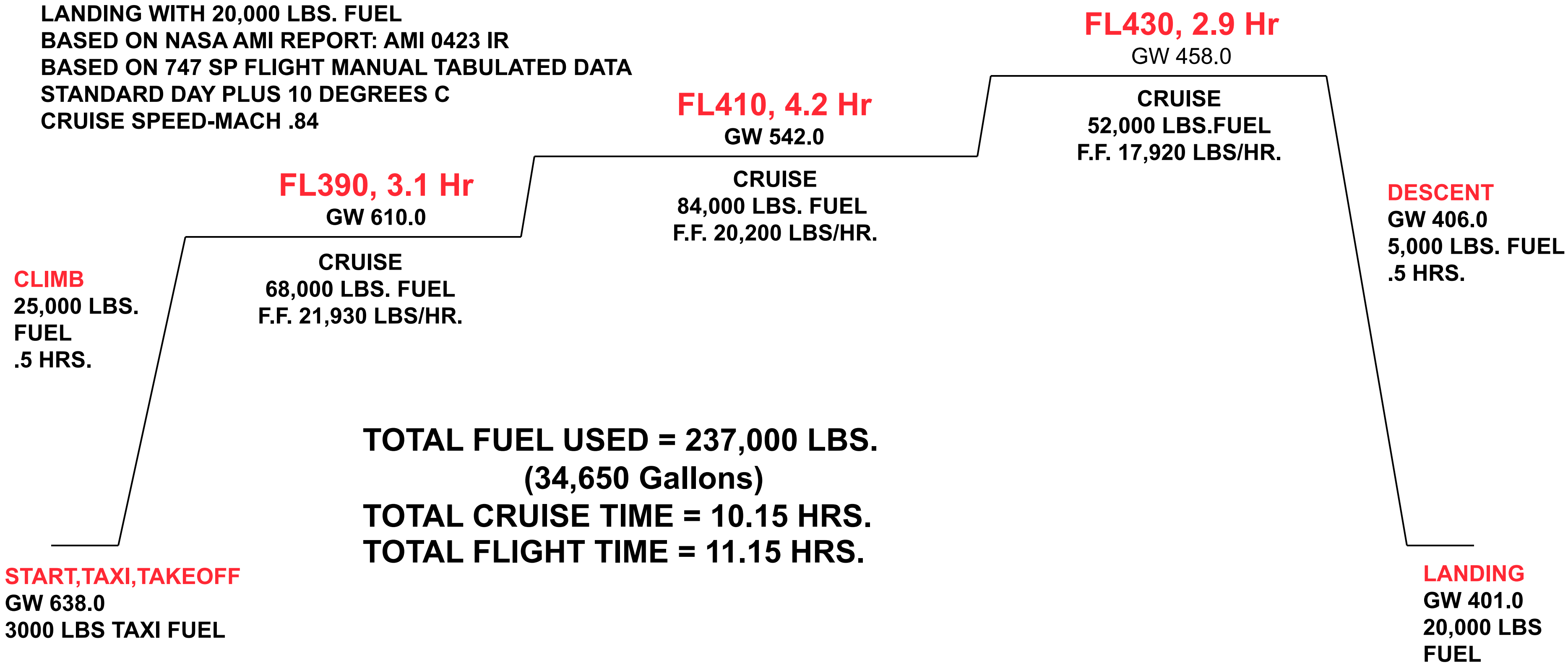
TOTAL FUEL USED = 169,000 LBS.
(24,708 Gallons)
TOTAL CRUISE TIME = 7.05 HRS.
TOTAL FLIGHT TIME = 8.05 HRS

Flight Profile 2

Performance with P&W JT9D-7J Engines: Observations - start FL390, duration 10.2 Hr

ASSUMPTIONS

ZFW 381,000 LBS.
ENGINES OPERATE AT 95% MAX CONT THRUST AT CRUISE
25,000 LBS. FUEL TO FIRST LEVEL OFF
CLIMB TO FIRST LEVEL-OFF AT MAX CRUISE WT
LANDING WITH 20,000 LBS. FUEL
BASED ON NASA AMI REPORT: AMI 0423 IR
BASED ON 747 SP FLIGHT MANUAL TABULATED DATA
STANDARD DAY PLUS 10 DEGREES C
CRUISE SPEED-MACH .84



TOTAL FUEL USED = 237,000 LBS.
(34,650 Gallons)
TOTAL CRUISE TIME = 10.15 HRS.
TOTAL FLIGHT TIME = 11.15 HRS.

DEFINITIONS

Spot market – refers to the one-time sale of a quantity of product "on the spot," in practice typically involving quantities in thousands of barrels at a convenient transfer point, such as a refinery, port, or pipeline junction. Spot prices are commonly collected and published by a number of price reporting services.

FOB stands for "Free On Board". Indicating "FOB" means that the seller pays for transportation of the goods to the port of shipment, plus loading costs. The buyer pays freight, insurance, unloading costs and transportation from the arrival port to the final destination. A trade term requiring the seller to deliver goods on board a vessel designated by the buyer. The seller fulfills its obligations to deliver when the goods have passed over the ship's rail.

The SOFIA Community Task Force (SCTF) - Members

Dana Backman: SOFIA

Eric Becklin: USRA SOFIA, University of California Los Angeles

Ed Erickson: SOFIA

Bob Gehrz (Leader): University of Minnesota

Paul Hertz: NASA Headquarters

Bob Joseph: University of Hawaii, Institute for Astronomy

Dan Lester: University of Texas

Margaret Meixner: NASA GSFC

Jay Norris: NASA ARC

Tom Roellig: NASA ARC

G[illegible]ren Sandell: SOFIA

Xander Tielens: NASA ARC

SI PI's/designated representatives

The Mission of the SCTF

The objectives of the Stratospheric Observatory for Infrared Astronomy (SOFIA) Community Task Force (SCTF) are to:

- ***Inform and engage the astronomical community in planning for the SOFIA General Observer (GO) science program***
- ***Develop a long-range science plan that will realize the potential of SOFIA as a premier observatory and as a platform for developing forefront technology***