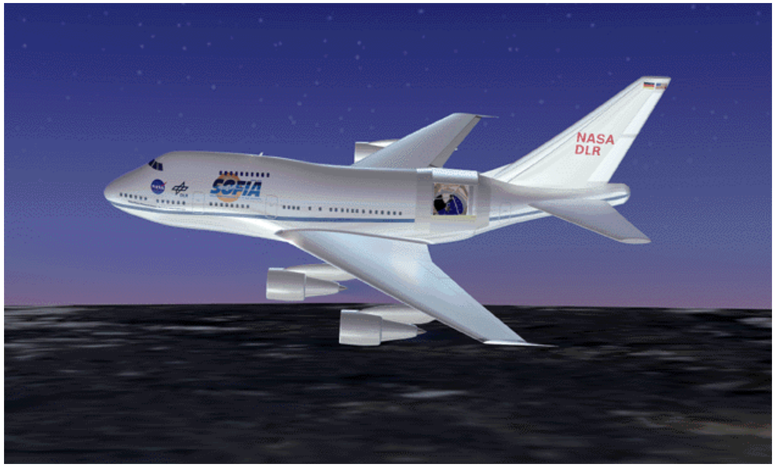
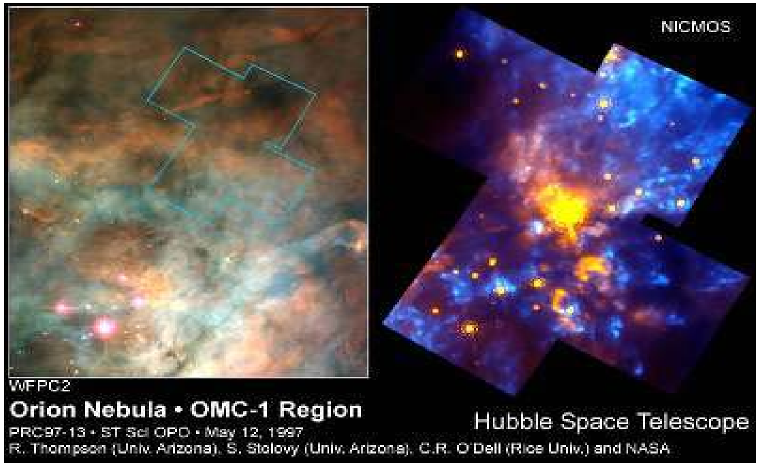
The Stratospheric Observatory for Infrared Astronomy (SOFIA)





R. D. Gehrz

Lead, SOFIA Community Task Force

Department of Astronomy, University of Minnesota

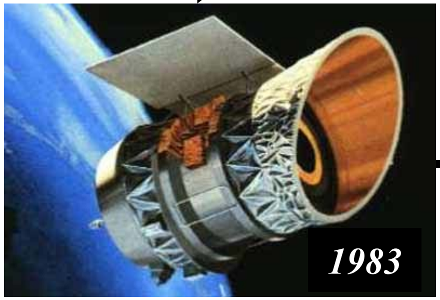
Outline

- SOFIA Heritage and Context
- SOFIA Description and Status Report
- SOFIA Performance Specifications
- SOFIA Science
- SOFIA Schedule and Opportunities for Collaboration
- Summary

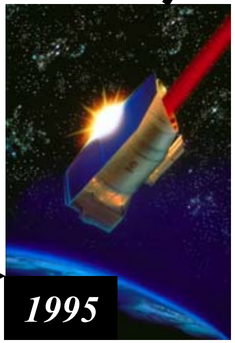
The History of Flying Infrared Observatories

NASA Lear Jet Observatory

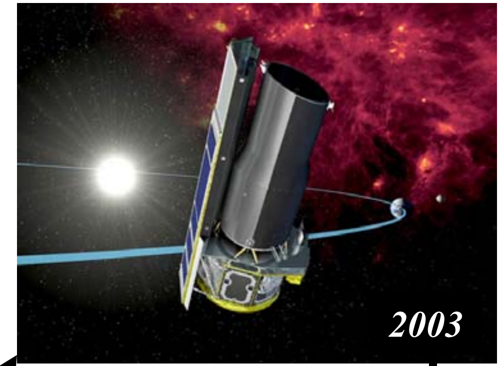
NASA Kuiper Airborne Observatory (KAO)



NASA Infrared Astronomical Satellite (IRAS)



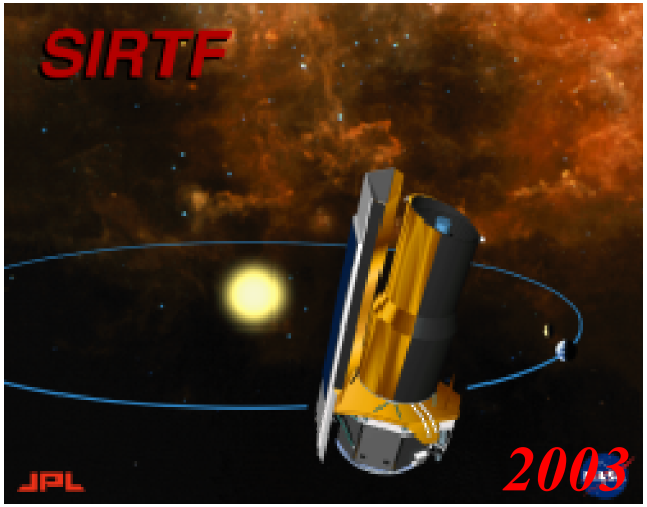
ESA Infrared Space Observatory (ISO)

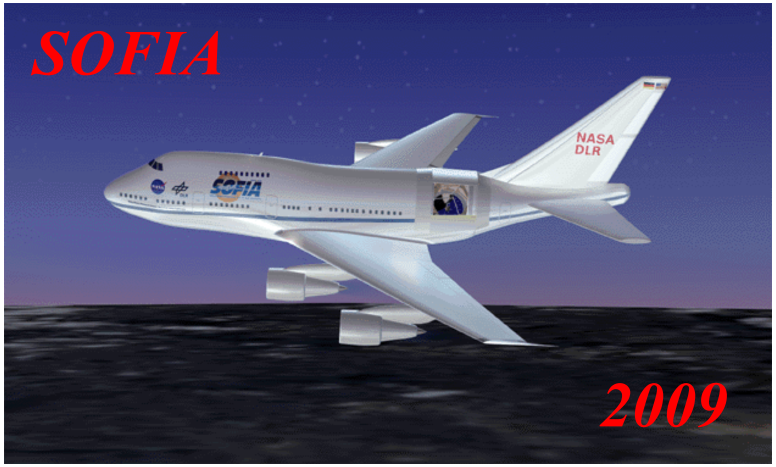


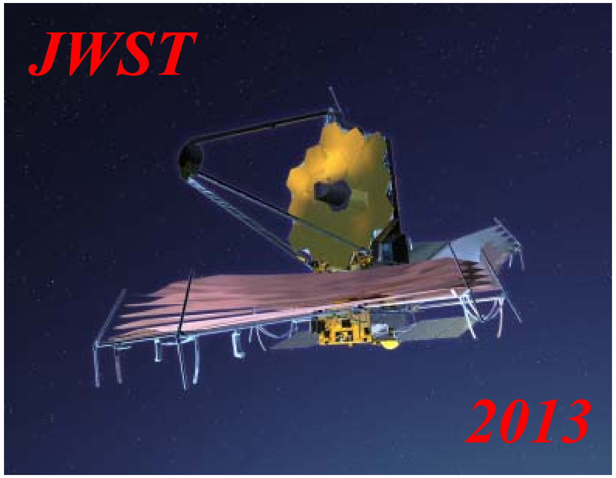
NASA Spitzer Space Telescope

NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)

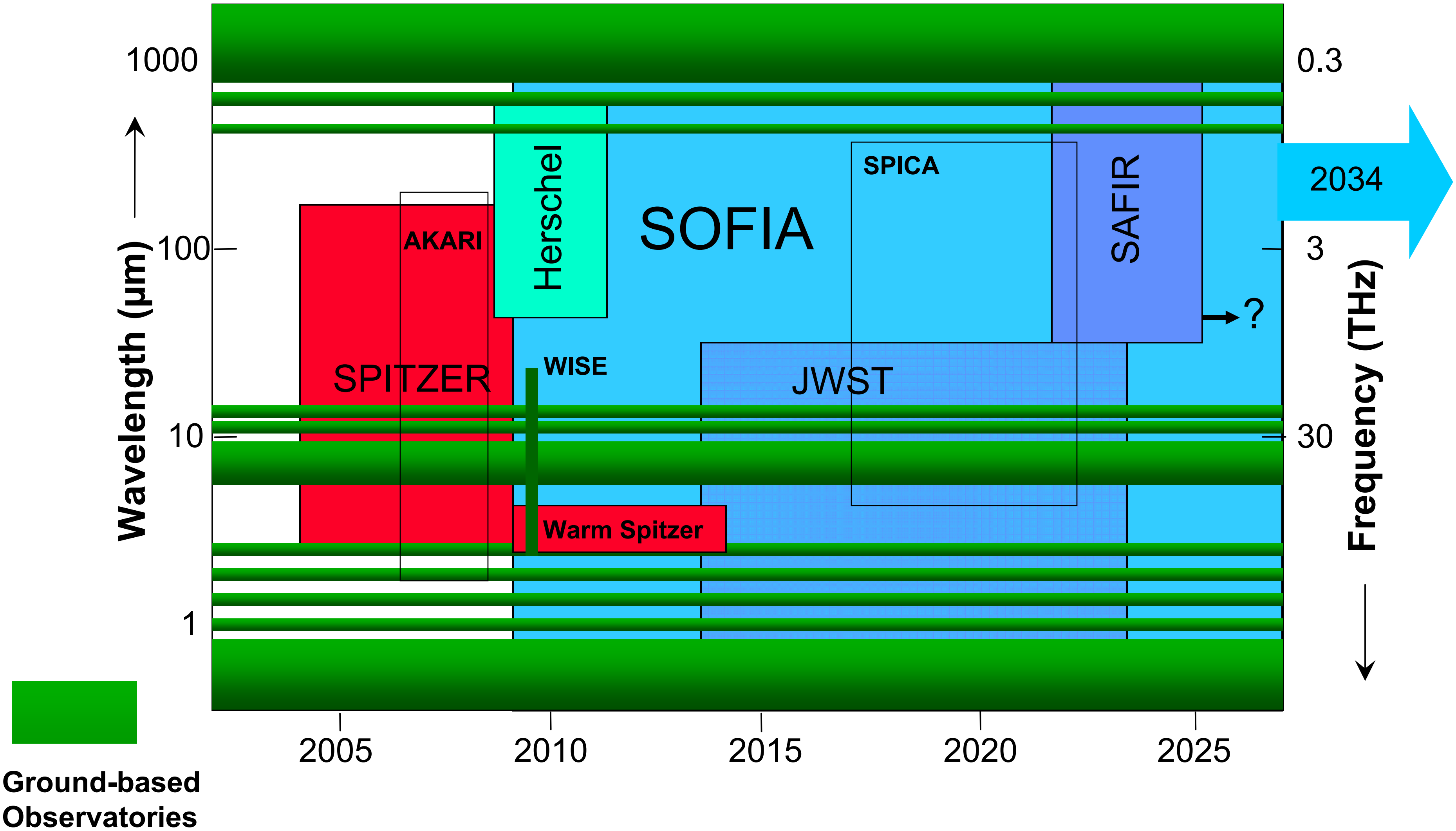
SOFIA and its Companions in Space



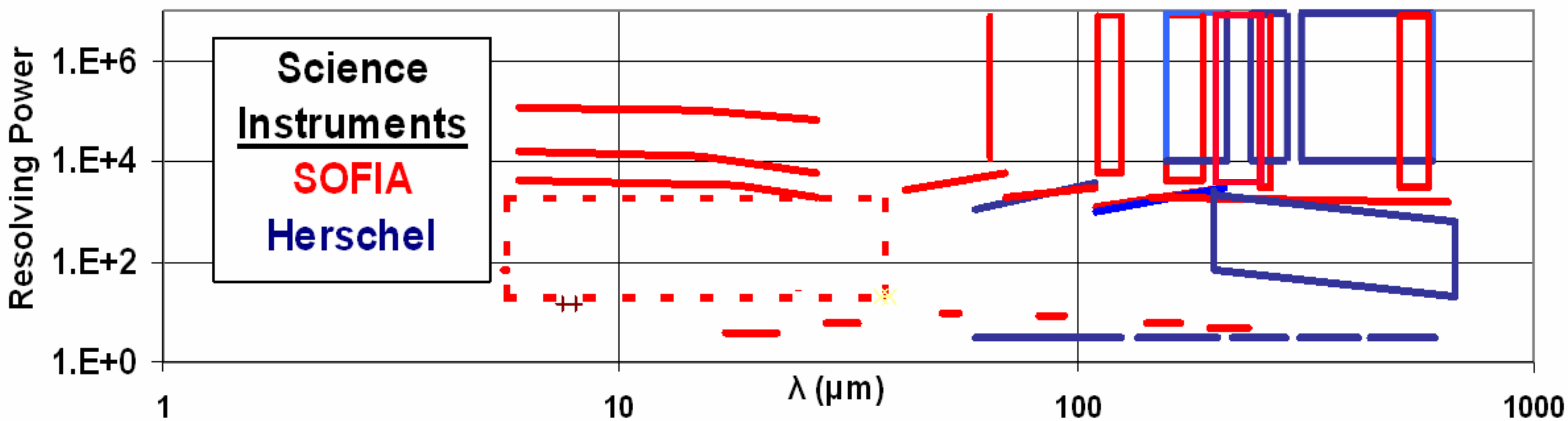




SOFIA and Major IR Imaging/Spectroscopic Space Observatories



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

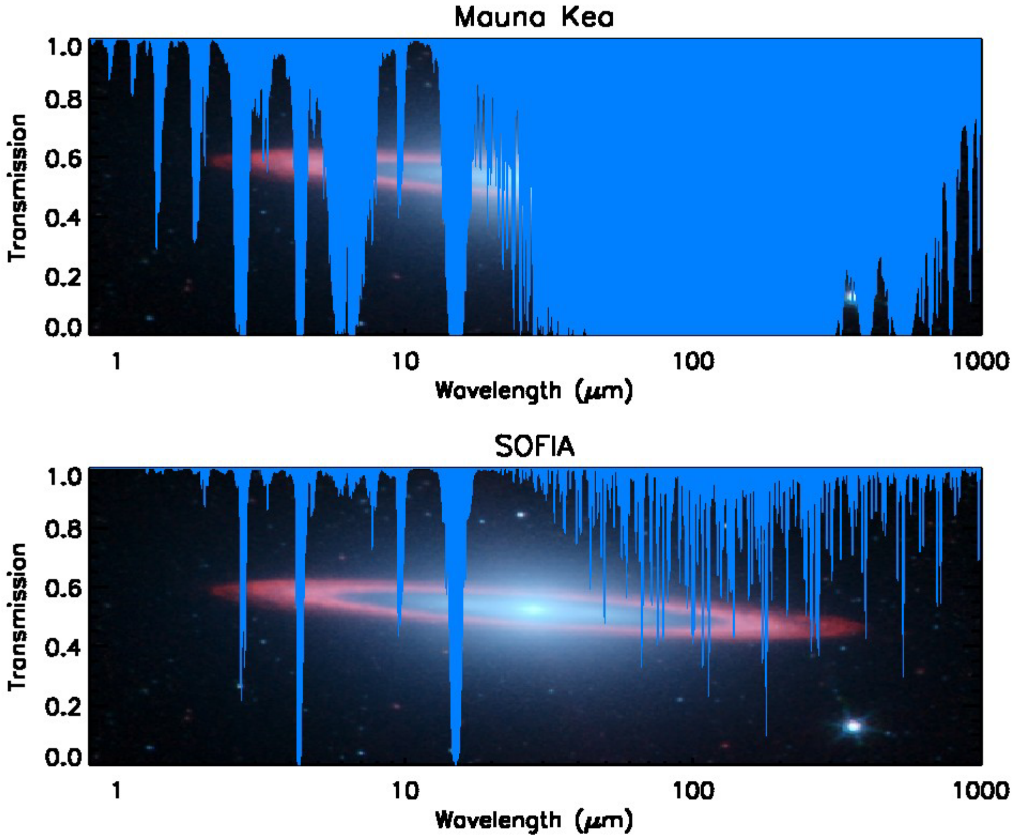
October 29, 2008

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

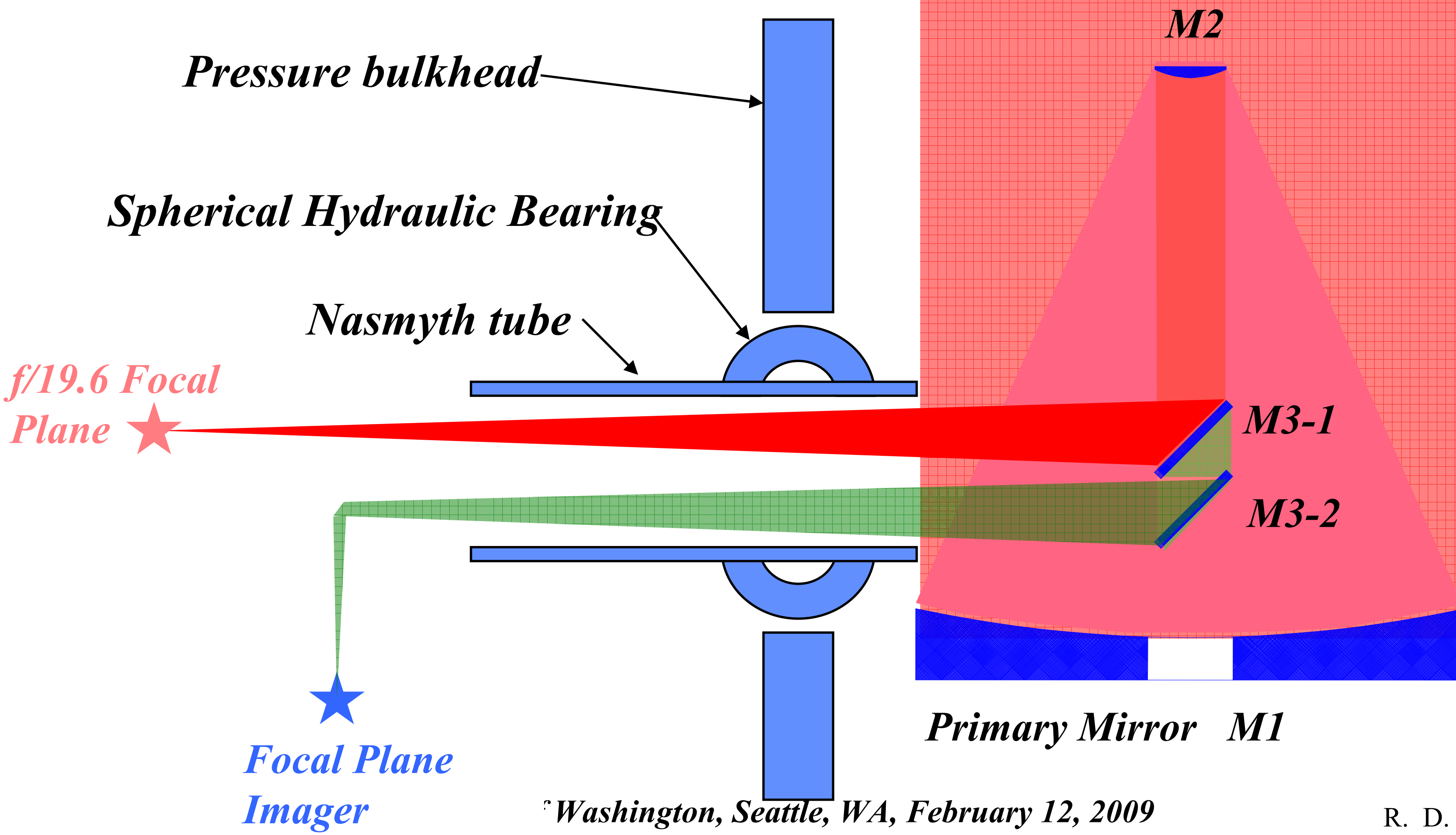
The Advantages of SOFIA

- *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*

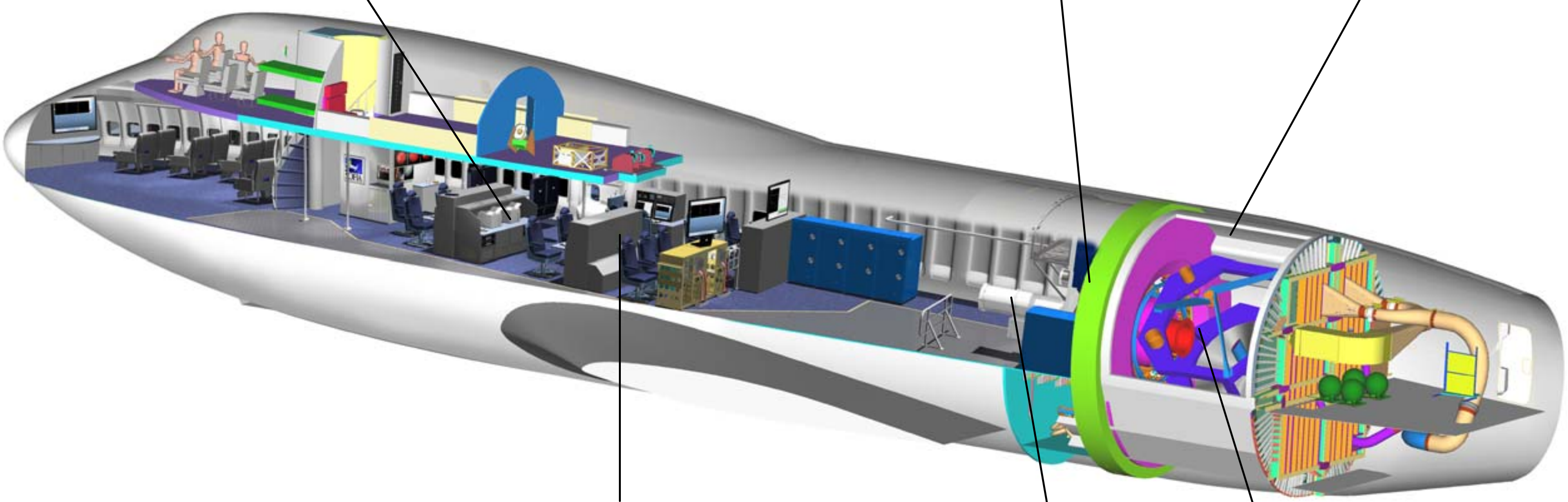


Nasmyth: Optical Layout

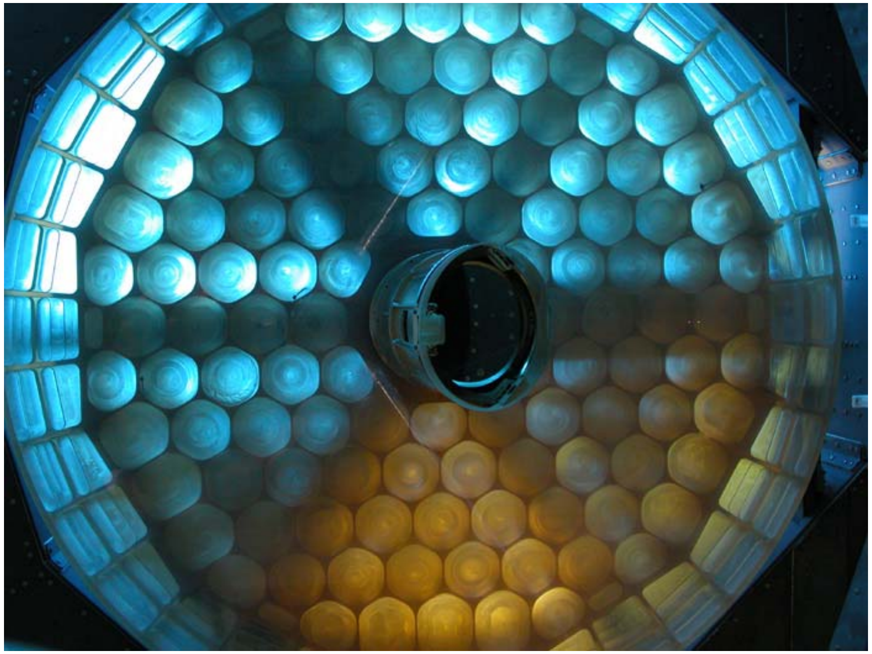
Observers in pressurized cabin have ready access to the focal plane



The SOFIA Observatory

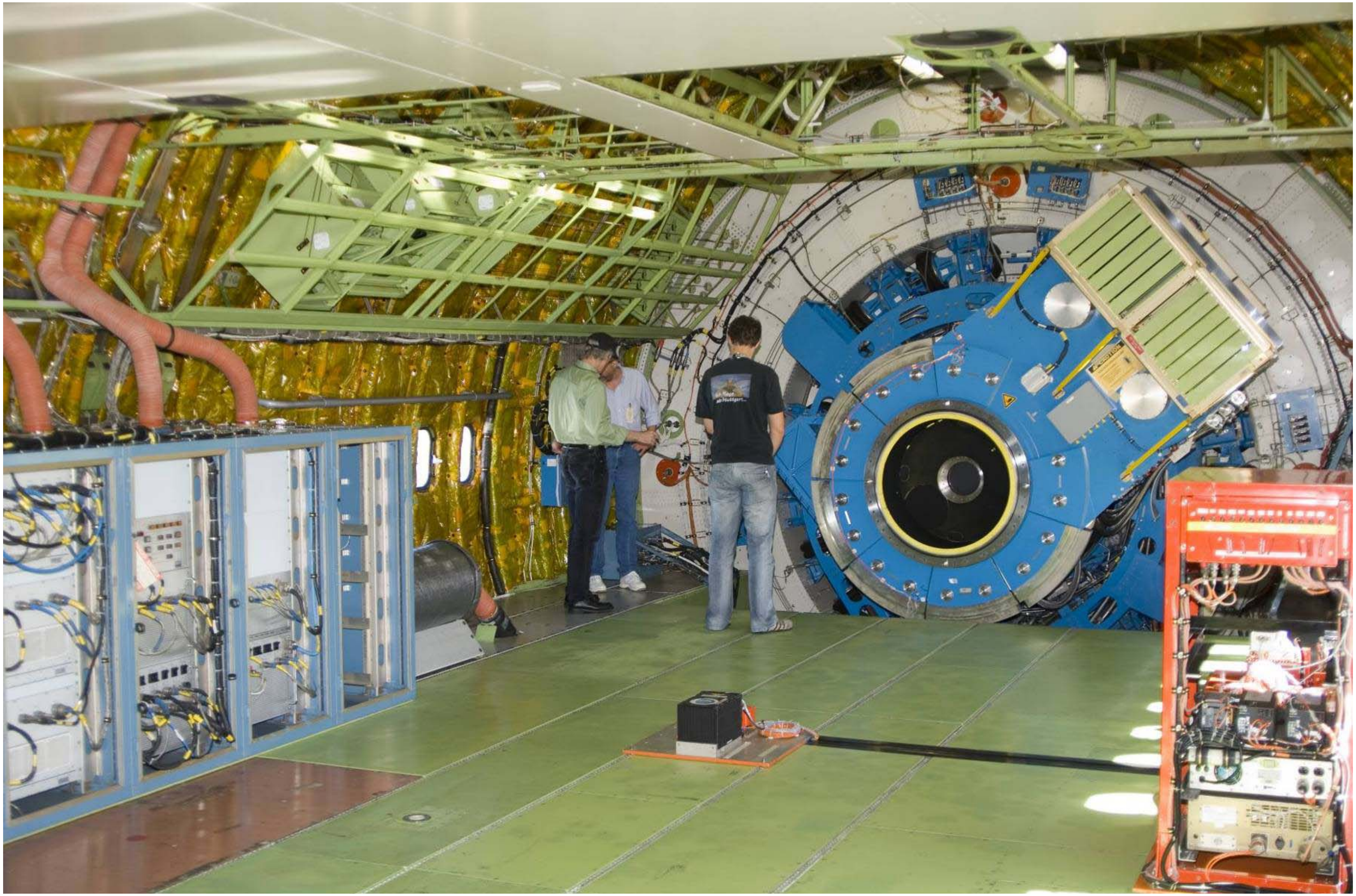


The Un-Aluminized Primary Mirror Installed



Primary Mirror Installed Oct. 8, 2008

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

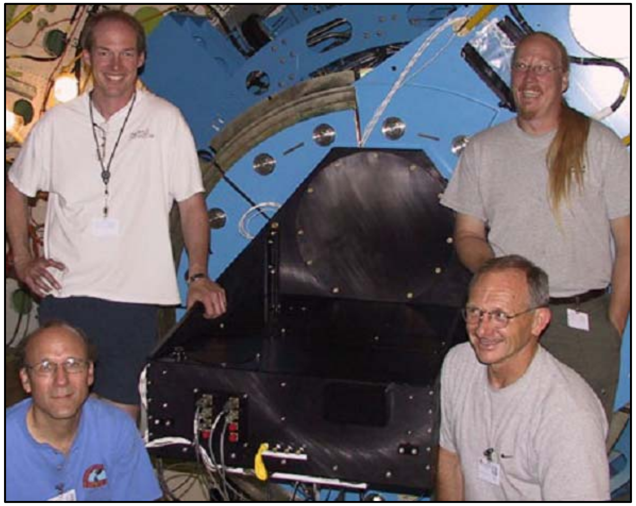
SOFIA's First-Generation Instruments

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*

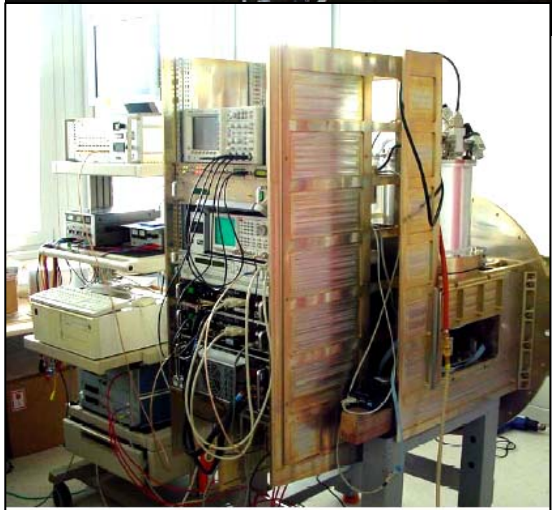
Four First Light Instruments



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

Working/complete FLITECAM instrument at Lick in 2004/5

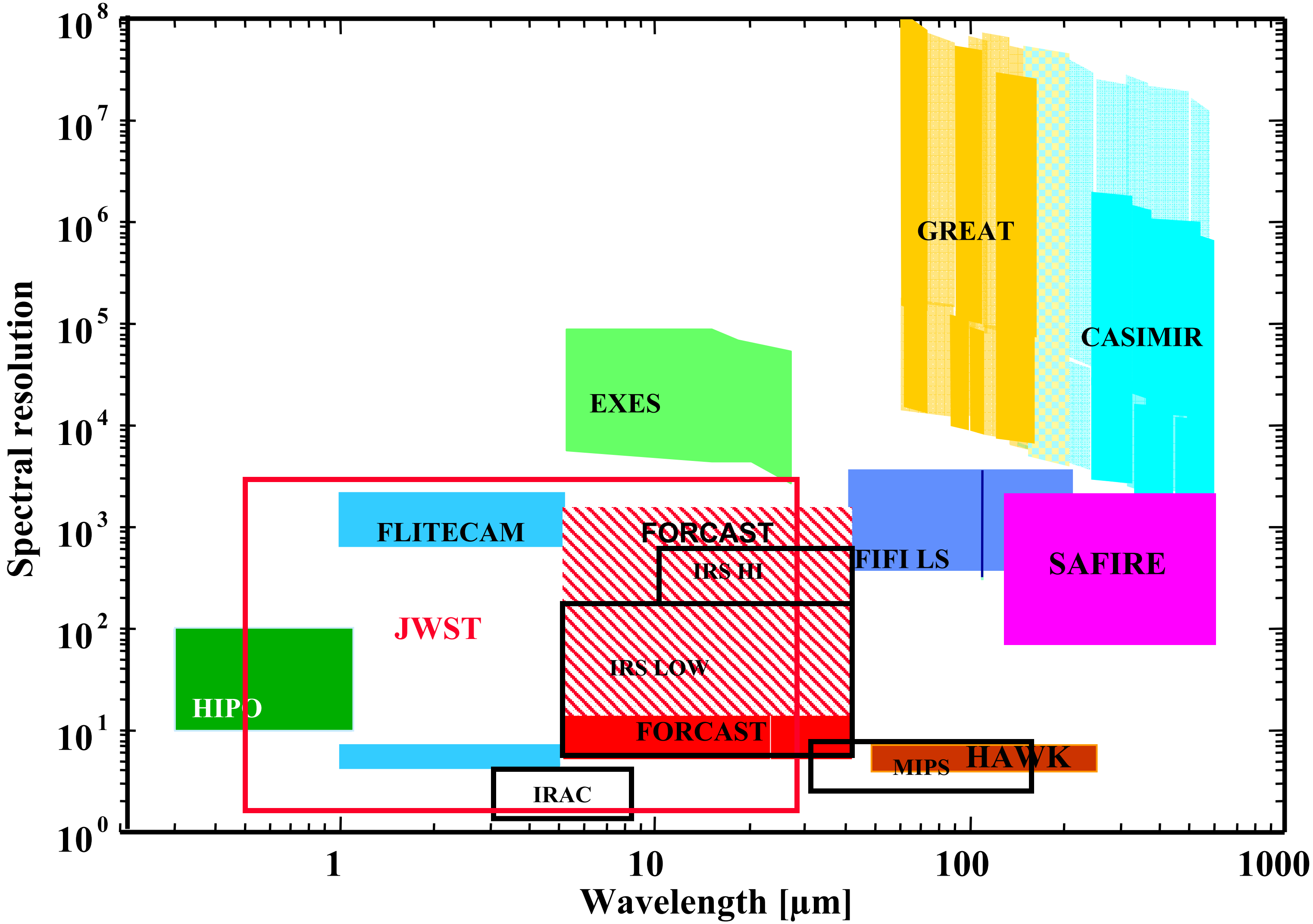
Working FORCAST instrument at Palomar in 2005



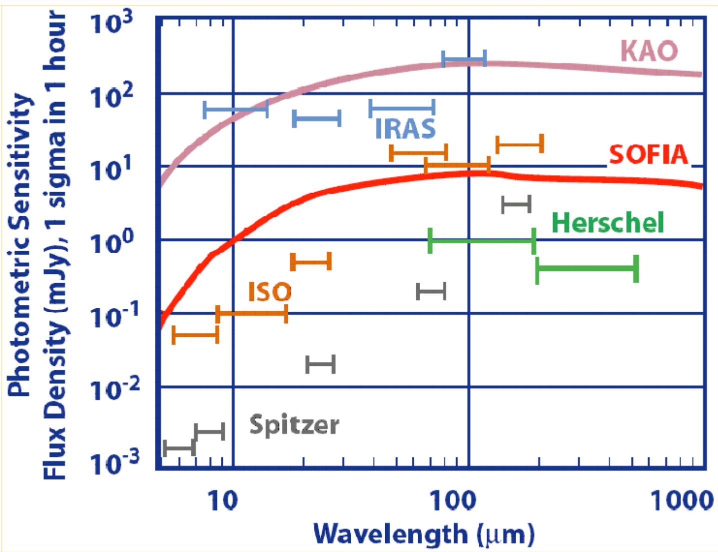
Lab-picture of GREAT equipped with the KOSMA 1.9THz channel

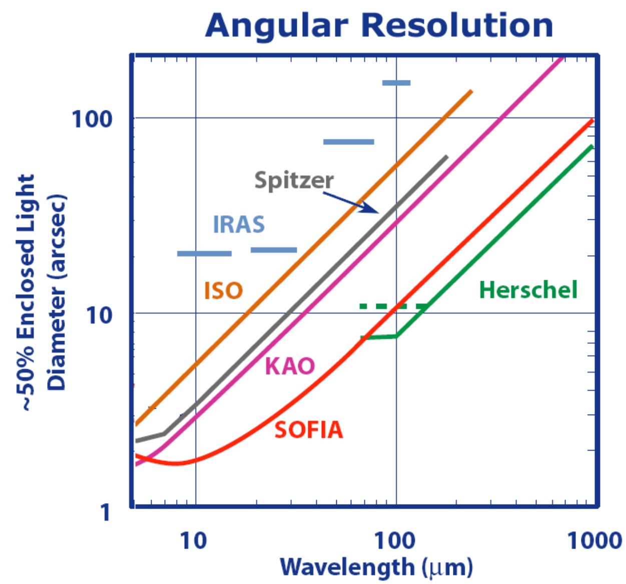
Successful lab demonstration of GREAT in July 2005

SOFIA First Generation Spectroscopy



Photometric Sensitivity and Angular resolution

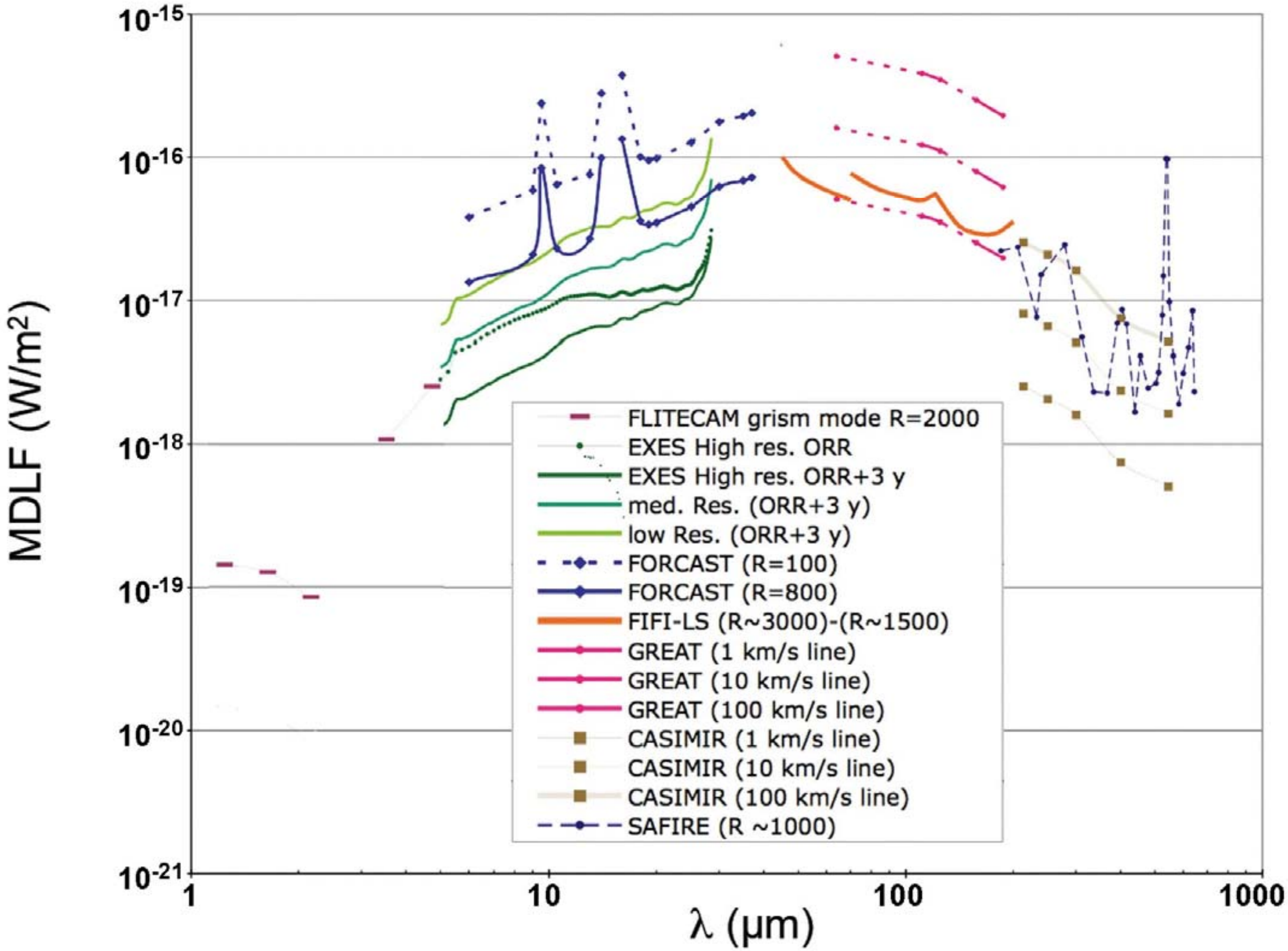




SOFIA is as sensitive as ISO

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)



SOFIA Addresses Key Science Questions

Stellar Astrophysics

- How does the ISM turn into stars and planets?
- How do dying stars enrich the ISM? What becomes of their ashes?

Planetary Science

- What are dwarf planets? How do they relate to solar system formation?
- Are biogenic molecules made in space? Are they in other solar systems?

Extragalactic Astrophysics

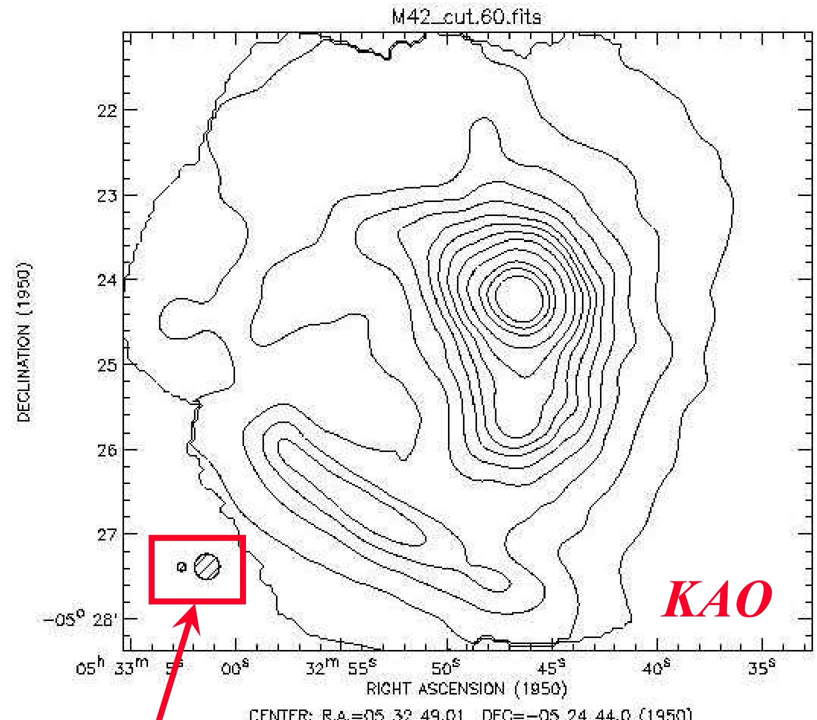
- What powers the most luminous galaxies? How do they evolve?
- What is a massive black hole doing at the center of our Galaxy?

Objects of Opportunity

- Bright comets, eruptive variable stars, classical novae, supernovae, occultations, transits of extra-solar planets

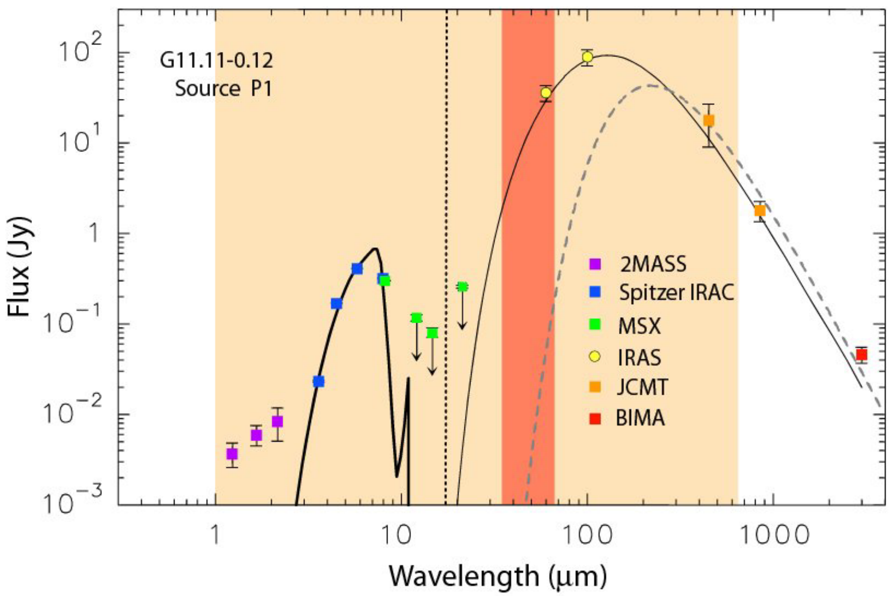
SOFIA and Regions of Star Formation

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

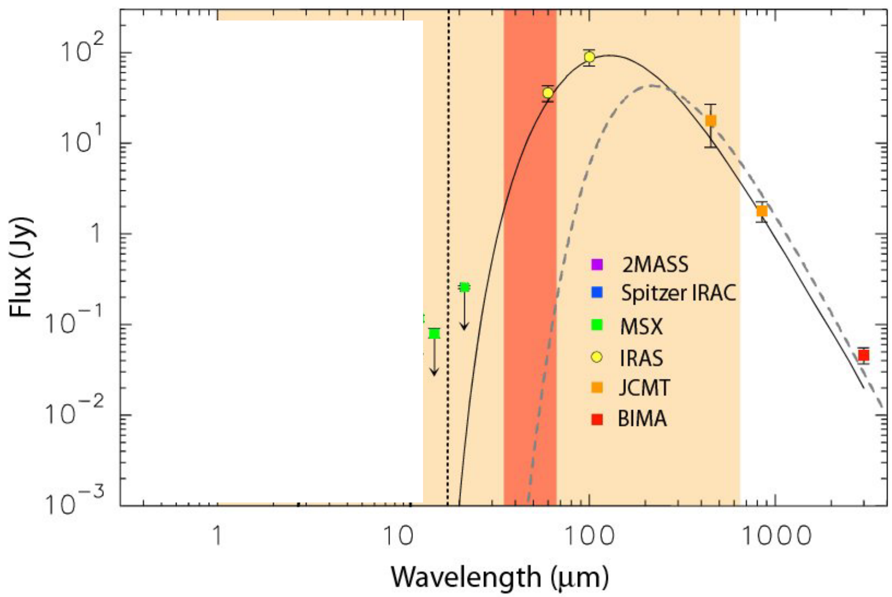


With 9 SOFIA beams for every 1 KAO beam, SOFIA imagers/HI-RES spectrometers can analyze the physics and chemistry of individual protostellar condensations where they emit most of their energy and can follow up on HERSCHEL discoveries.

Sources Embedded in Massive Cloud Cores

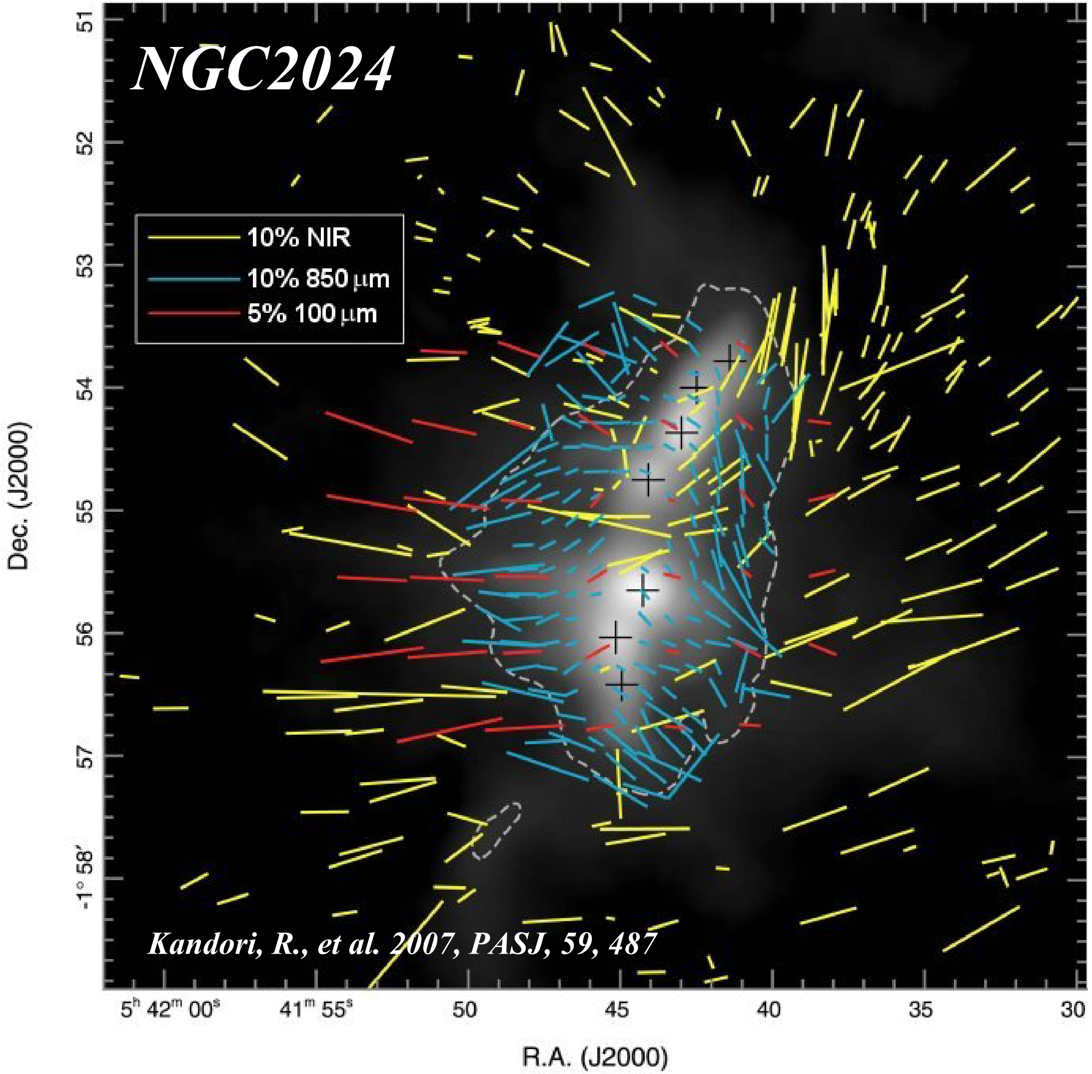


- *In highly obscured objects, no mid-IR source may be detectable*



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

Magnetic Fields in Massive Star Forming Regions

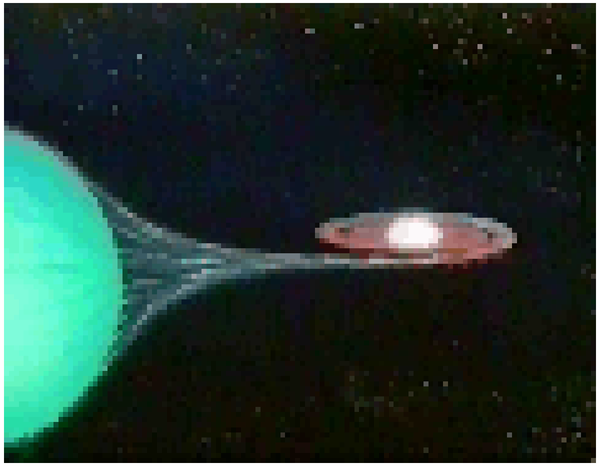


Within the dashed contour, NIR and submm disagree on field direction. NIR does not probe the dense material. FIR will probe warm, dense material.

IRSF/SIRIUS and JCMT/SCUBA data

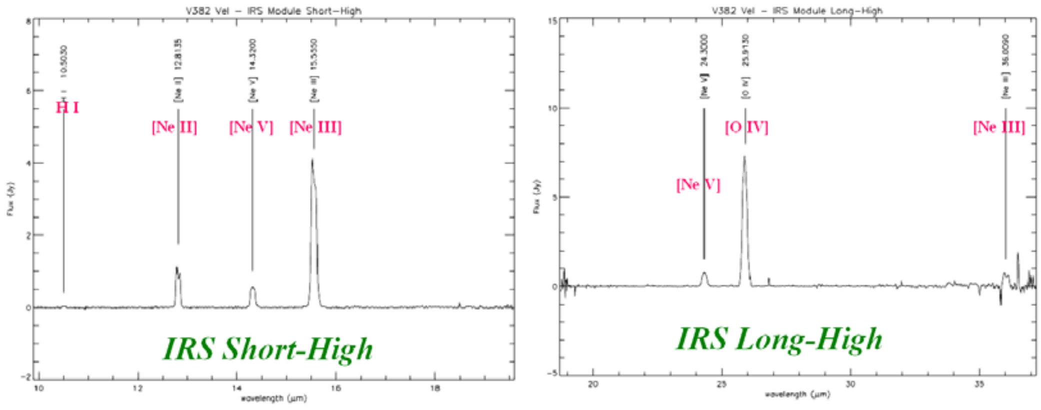
SOFIA and Classical Nova Explosions

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]

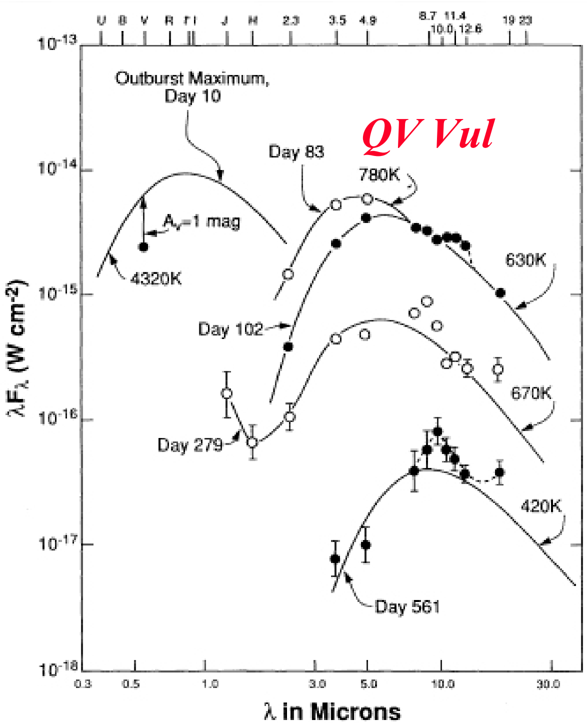


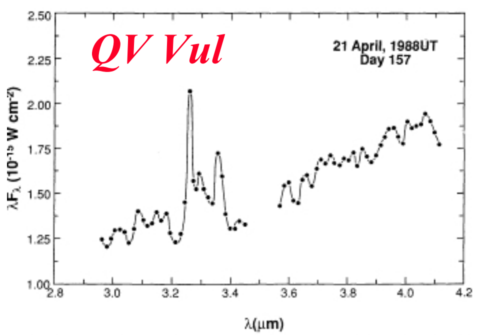
- ***Gas phase abundances of CNOMgNeAl***
- ***Contributions to ISM clouds and the primitive Solar System***
- ***Kinematics of the Ejection***

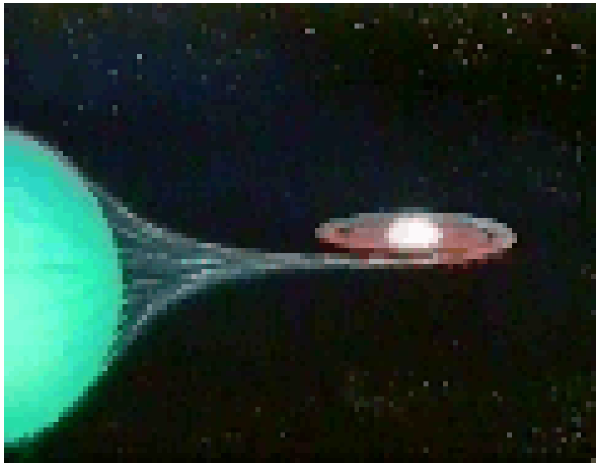
SOFIA and Classical Nova Explosions

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

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





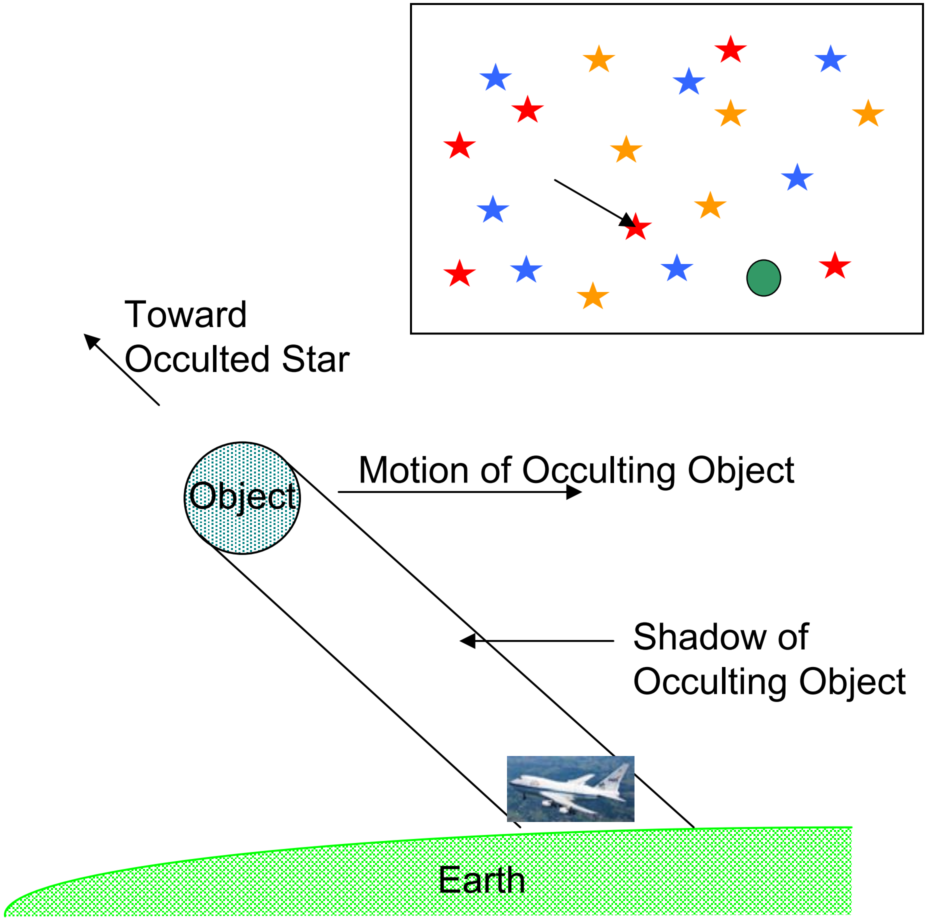


- *Stardust formation, mineralogy, and abundances*
- *SOFIA's spectral resolution and wavelength coverage is required to study amorphous, crystalline, and hydrocarbon components*
- *Contributions to ISM clouds and the Primitive Solar System*

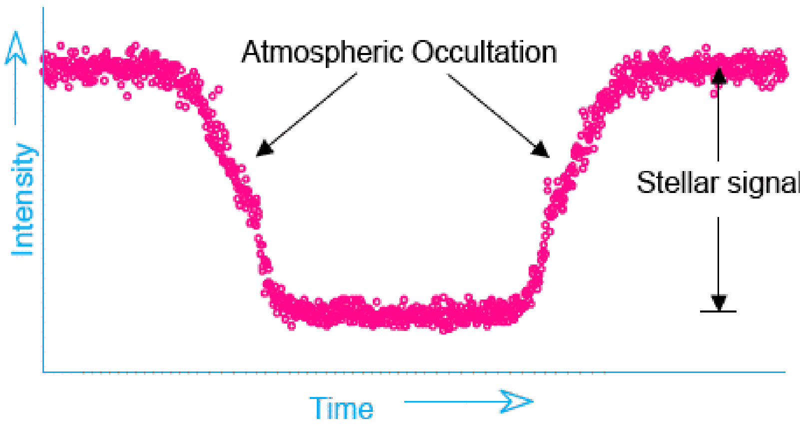
Occultation Astronomy with SOFIA

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.***

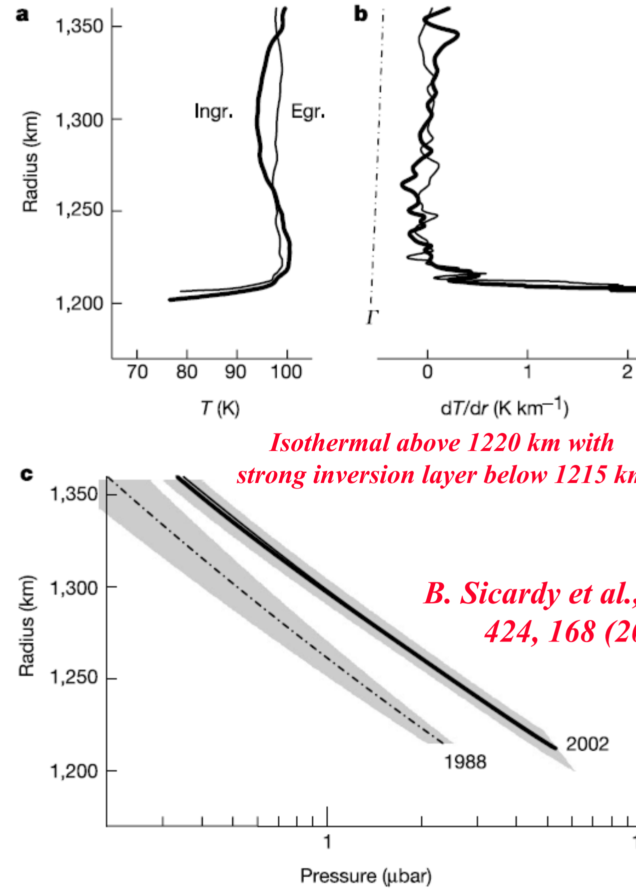


Occultations and Atmospheres



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)

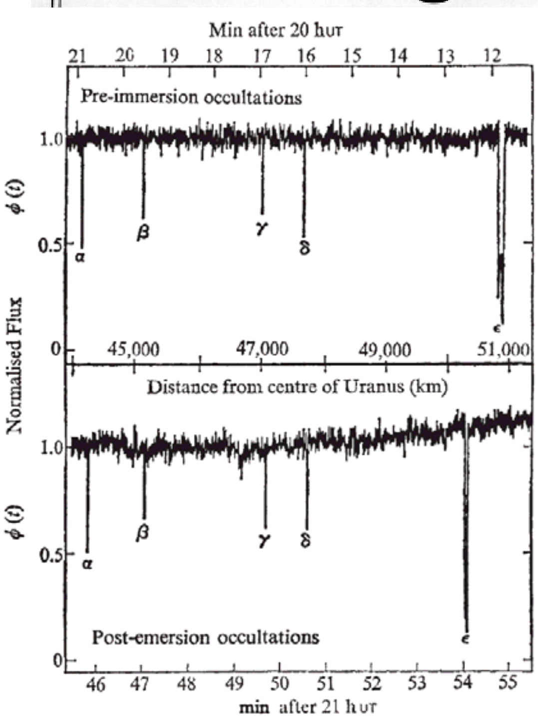
Figure 2 Temperature and pressure profiles of Pluto's atmosphere derived from the inversion of the P131.1 light curve. This inversion[17] assumes a spherically symmetric and transparent atmosphere. It first provides the atmospheric refractivity profile, then the density profile for a given gas composition, 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 Werner

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.



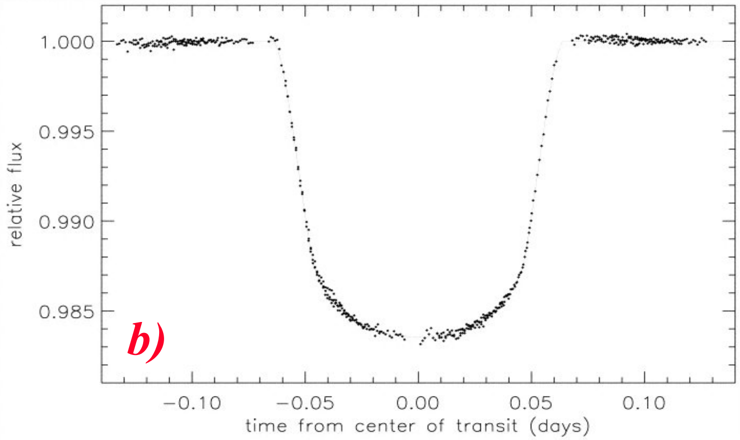
This occultation light curve observed on the KAO in 1977 shows the discovery of a five ring system around Uranus

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

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

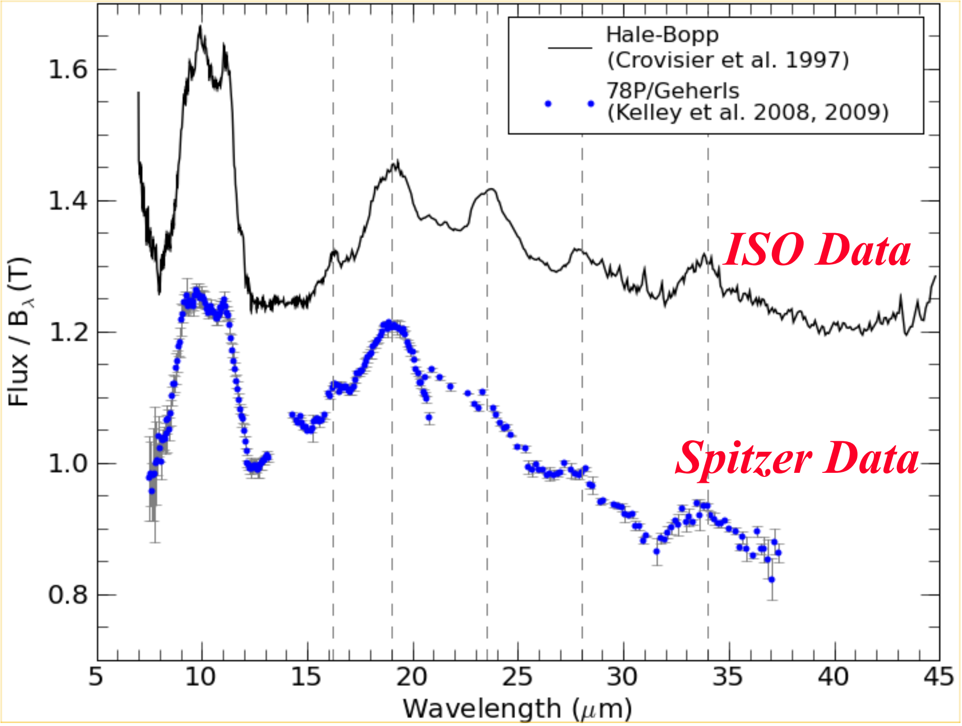
- Transits provide good estimates for the mass, size and density of the planet
- Transits may reveal the presence of, satellites, and/or planetary rings

Observing Comets in the IR with SOFIA

- *Comet nuclei, comae, tails, and trails emit primarily at the thermal IR wavelengths accessible with Spitzer (3-180 μm)*
- *Emission features from grains, ices, and molecular gases occur in the IR*
- *IR Space platforms (Spitzer, Herschel, 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?



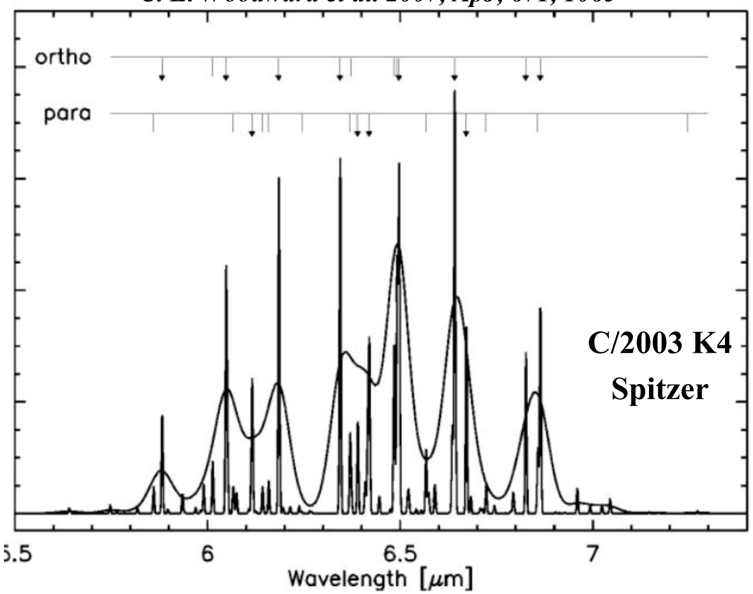
The vertical lines mark features of crystalline Mg-rich crystalline olivine (forsterite)

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

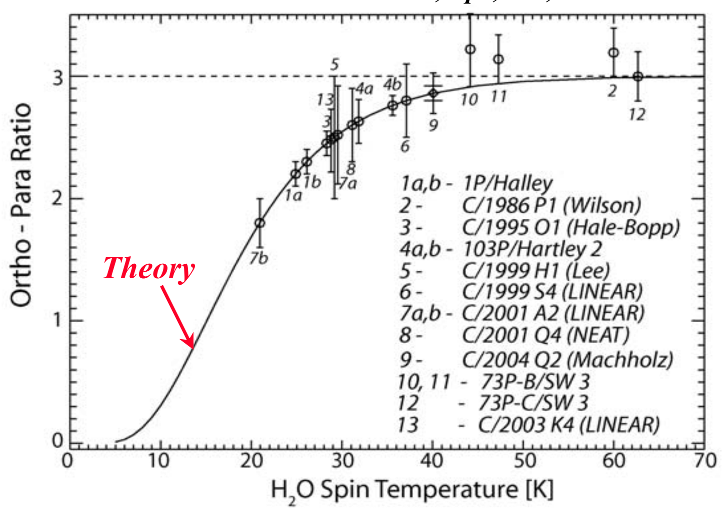
SOFIA and Comets: Gas Phase Constituents

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 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

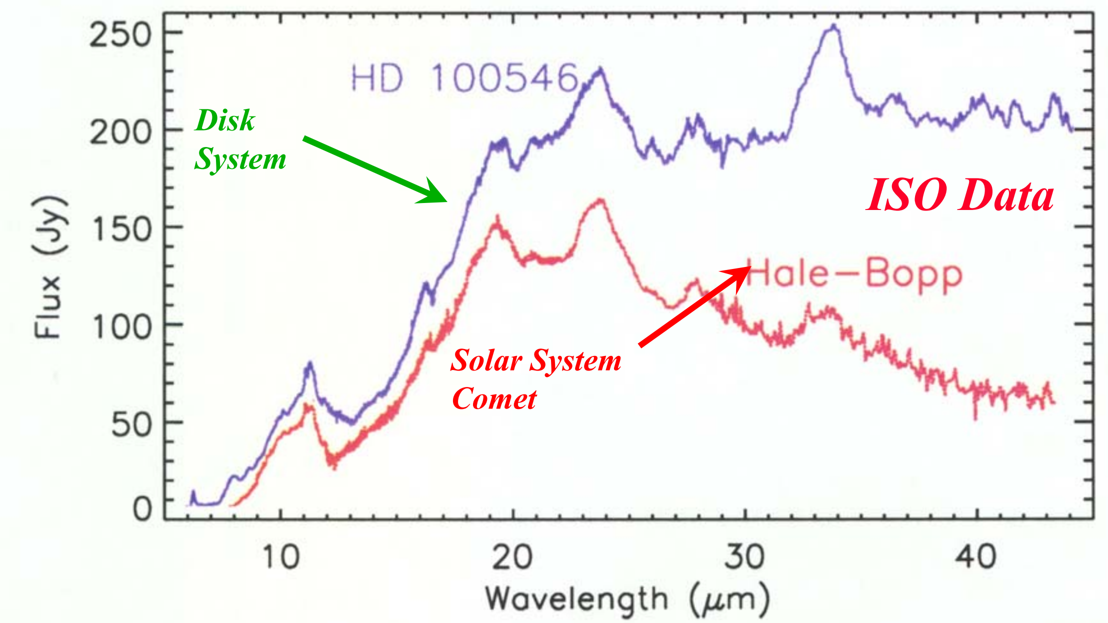
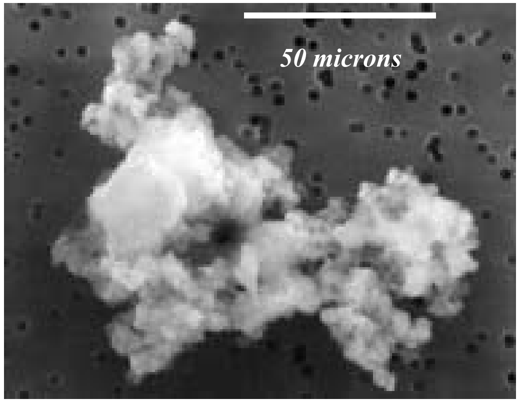


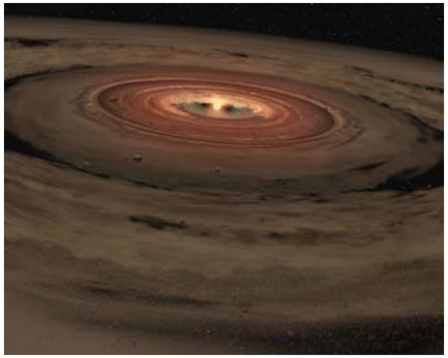
Image of Solar System IDP (Interplanetary Dust Particle)

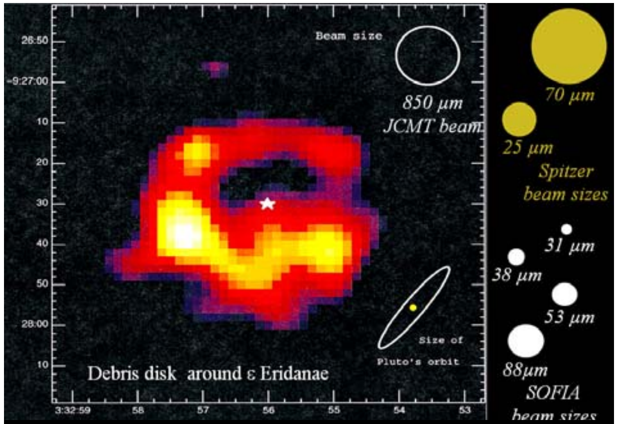


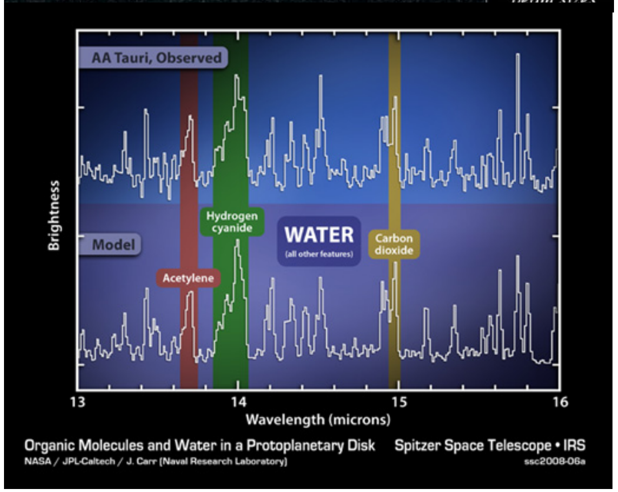
- *The silicate features in HD 100546 and C/1995 O1 Hale-Bopp are well-matched, suggesting that the grains in the stellar disk system and the small grains released from the comet nucleus are similar*

SOFIA and Extra-Solar Circumstellar Disks

What can SOFIA tell us about circumstellar disks?

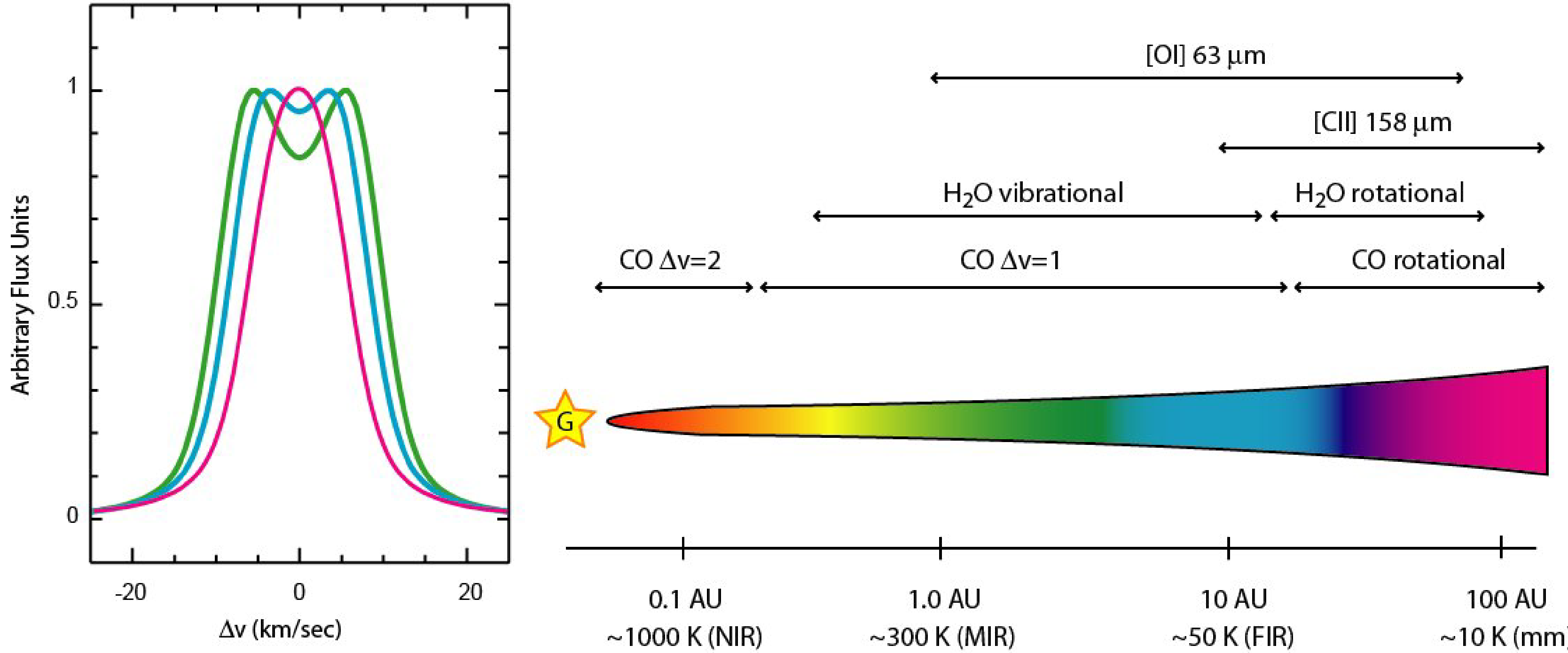






- *SOFIA imaging and spectroscopy can resolve disks to trace the evolution of the spatial distribution of the gaseous, solid, and icy gas and grain constituents*
- *SOFIA can shed light on the process of planet formation by studying the temporal evolution of debris disks*

How does the chemistry of disks vary with radius?

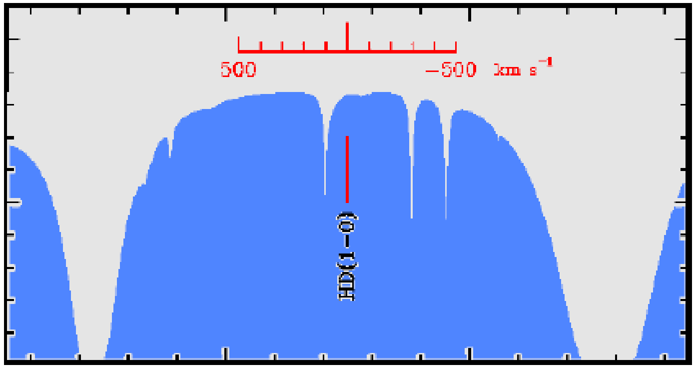


- ***High spectral resolution can determine where species reside in the disk; small radii produce double-peaked, wider lines.***
- ***Observing many sources at different ages in this way will trace the disk chemical evolution***

Cold Molecular Hydrogen using HD

How can SOFIA be used to study the cold molecular hydrogen abundance in the Galaxy using the 112 μm ground-state HD line?

- Deuterium is created in the Big Bang.
- Cold HD (T<50K) is a Proxy for cold molecular Hydrogen
- Cold HD can best be mapped in the 112 μm ground-state rotational line

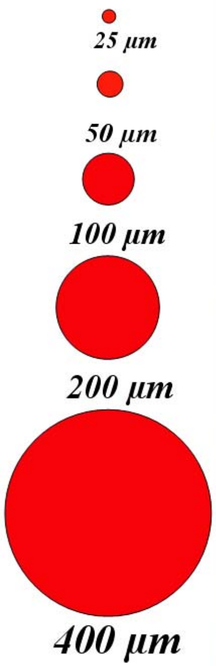


Atmospheric transmission around the HD line at 40,000 feet

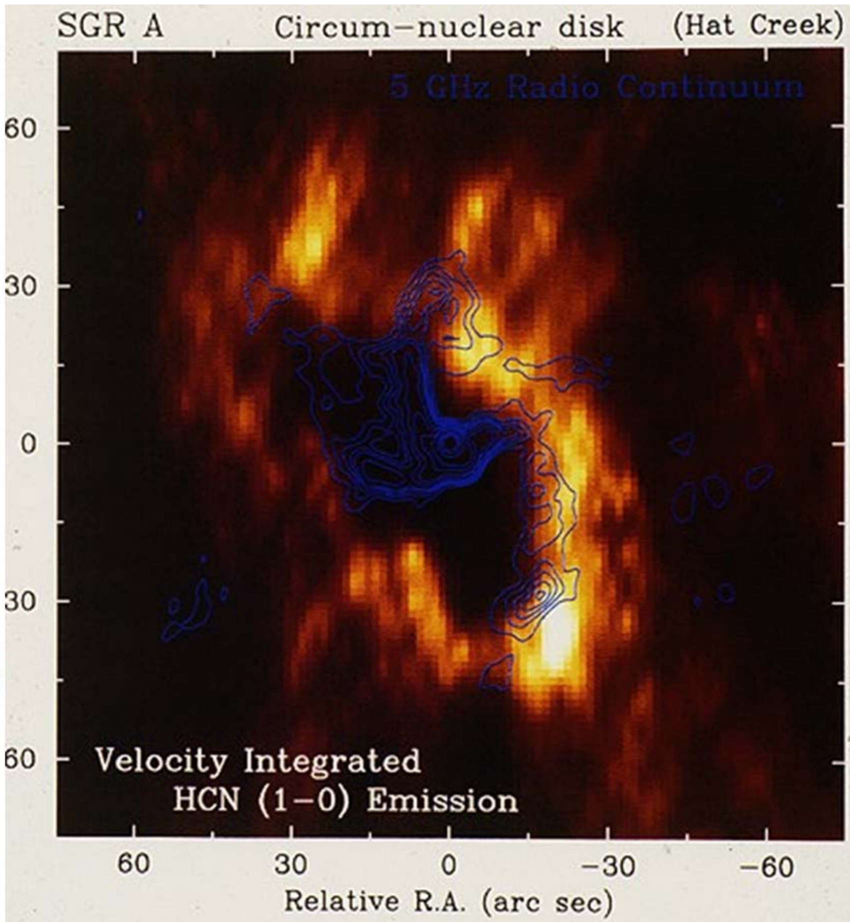
- A GREAT high resolution spectrometer study is possible given ISO detection of SGR B showing that HD column densities of ~ $10^{17} - 10^{18}$ can be detected
- This technique could be used to map the Galactic distribution of cold molecular gas the way that 21 cm is used to map the distribution of neutral hydrogen

SOFIA and the Black Hole at the Galactic Center

How will SOFIA study the massive 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*

Early General Observer Opportunities

- ***Open Door Flights* will begin at Palmdale in Summer of 2009**
- ***Early Short Science* in the winter of 2009-10 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 released in Jan 2009***
  - ***Final call to be released in Summer 2009***
  - ***Longer period (~15 Flights)***
  - ***Call will be for GO Science***

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*

Partnership Opportunity on SOFIA

- ***NASA is funding 80% of the program and the German space agency (DLR) is funding 20% of the program***
- ***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***

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's 9 First Generation Instruments

Instrument *	Type	λλ (μm)	Resolution	PI	Institution
HIPO %	fast imager	0.3 - 1.1	filters	E. Dunham	Lowell Obs.
FLITECAM %	imager/grism	1.0 - 5.5	filters/R~2E3	I. McLean	UCLA
FORCAST	imager/(grism?)	5.6 - 38	filters/(R~2E3)	T. Herter	Cornell U.
GREAT ¤	heterodyne receiver	158 - 187, 110 - 125, 62 - 65	R ~ 1E4 - 1E8	R. G□sten	MPIfR
CASIMIR ¤	heterodyne receiver	250 -264, 508 -588	R ~ 1E4 -1E8	J. Zmuidzinas	CalTech
FIFI LS ¤	imaging grating spectrograph	42 - 110, 110 - 210	R ~1E3 - 2E3	A. Poglitsch	MPE
HAWC ¤	imager	40 - 300	filters	D. A. Harper	Yerkes Obs.
EXES	imaging echelle spectrograph	4.5-28.3	R ~ 3E3 - 1E5	J. Lacy	U. Texas Austin
SAFIRE ¤	F-P imaging spectrometer	150 - 650	R ~ 1E3 - 2E3	H. Moseley	NASA GSFC

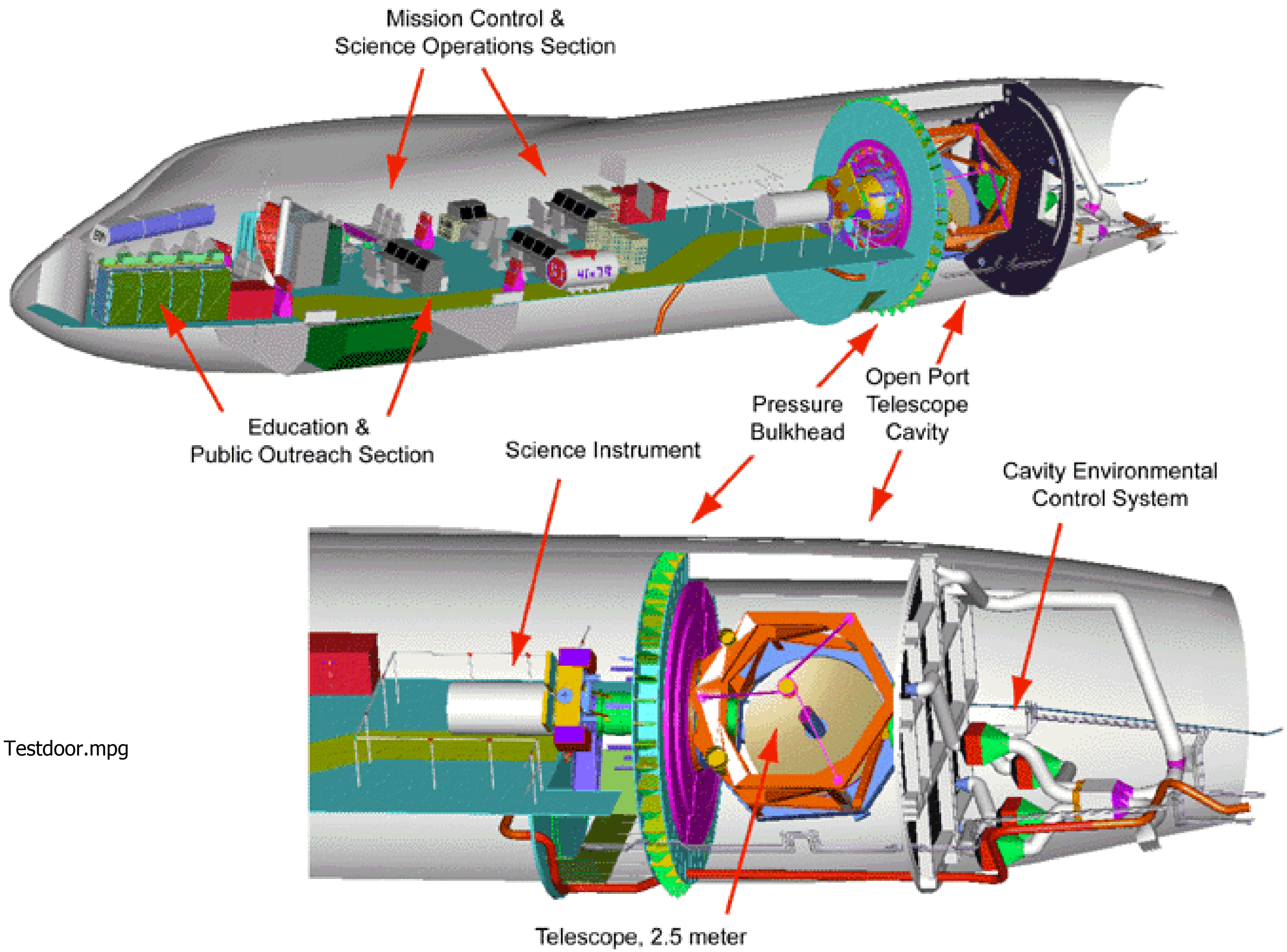
** Listed in approximate order of expected in-flight commissioning*

% Operational (August 2004)

§ Uses non-commercial detector/receiver technology

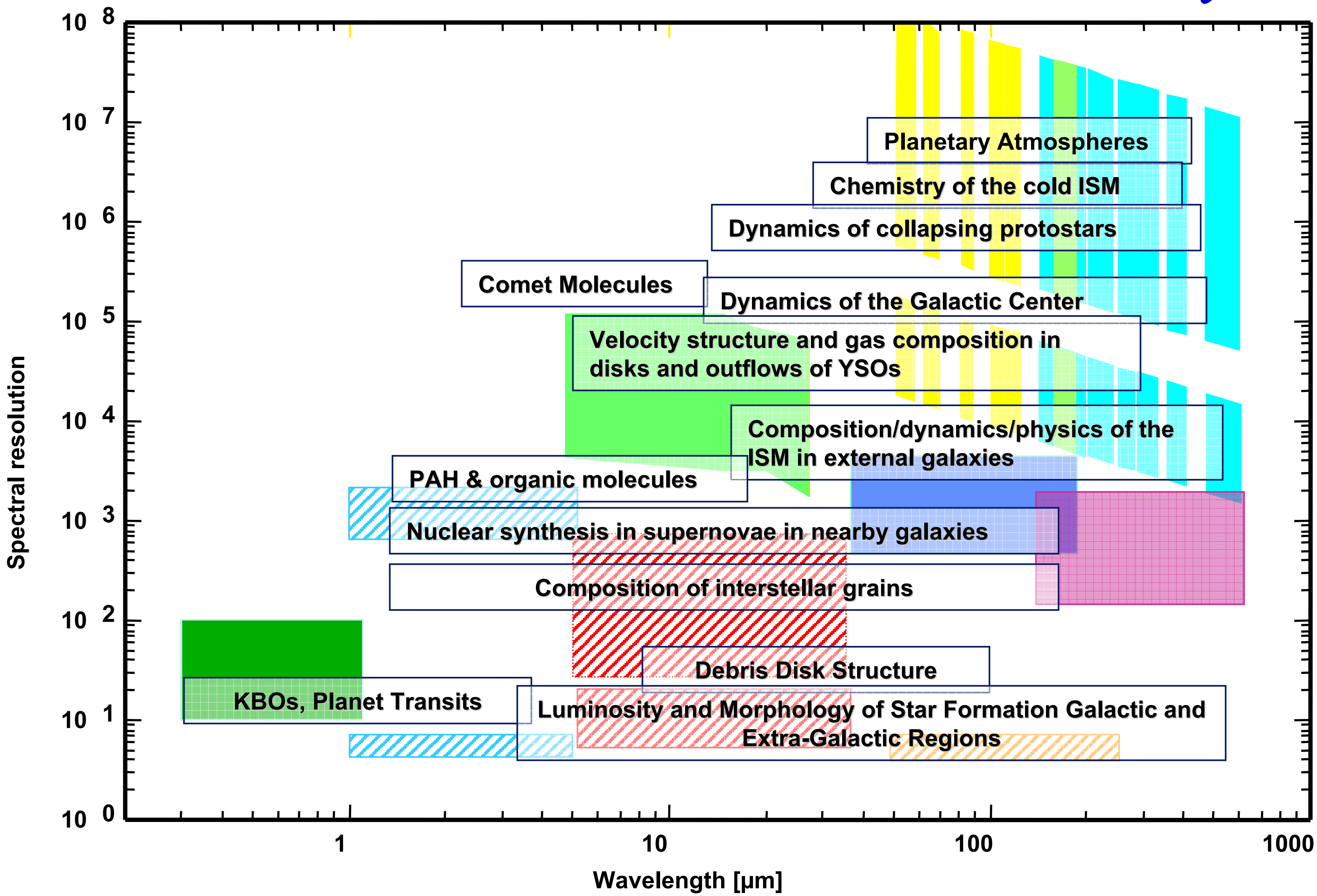
Layout of Personnel and Accomodations

(upper deck not shown)



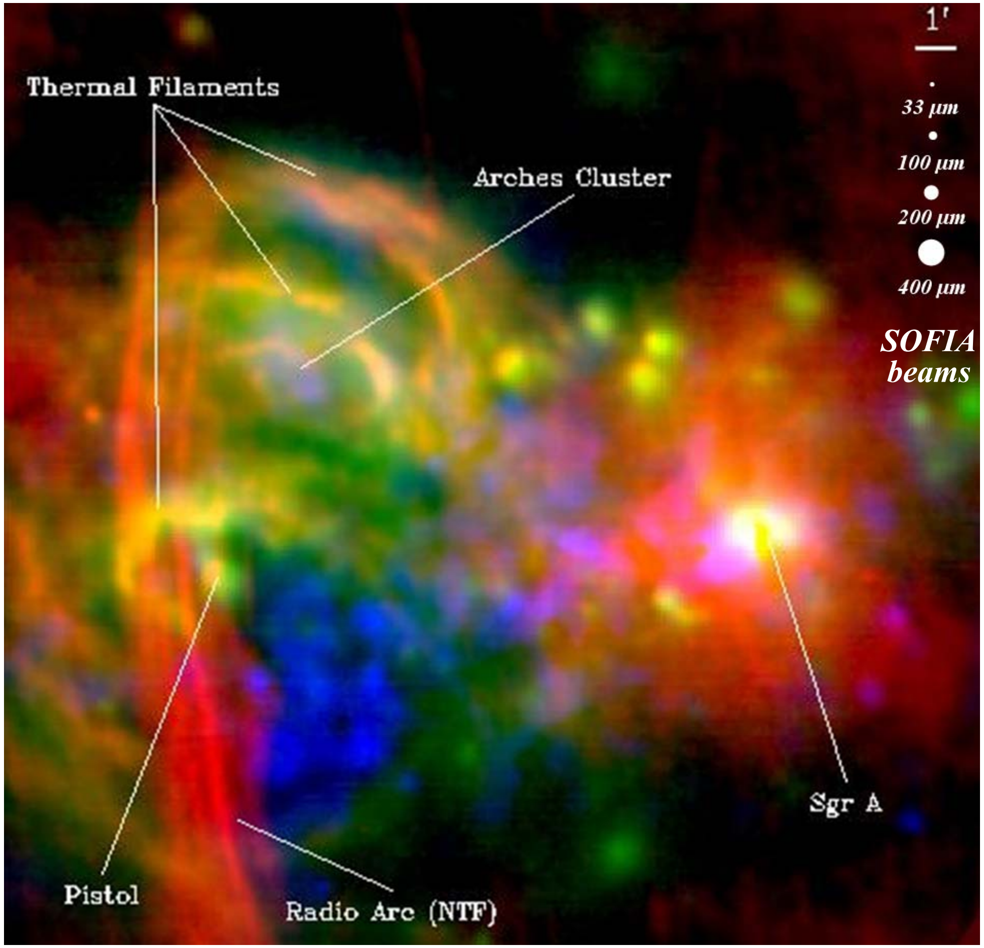
Testdoor.mpg

SOFIA: Science For the Whole Community



SOFIA and Activity in Galactic Nuclei

What can SOFIA see at the center of our Galaxy?



Red, 90 cm radio; green, mid-IR; blue, X-ray: Daniel Wang et al., University of Massachusetts HST OBSERVING PROGRAM 11120.

- *SOFIA imagers and spectrometers can resolve important structures at the center of the Galaxy*
- *An objective of SOFIA science is the identification of the stellar sources that excite and support the thermal arches near the Galactic Center*

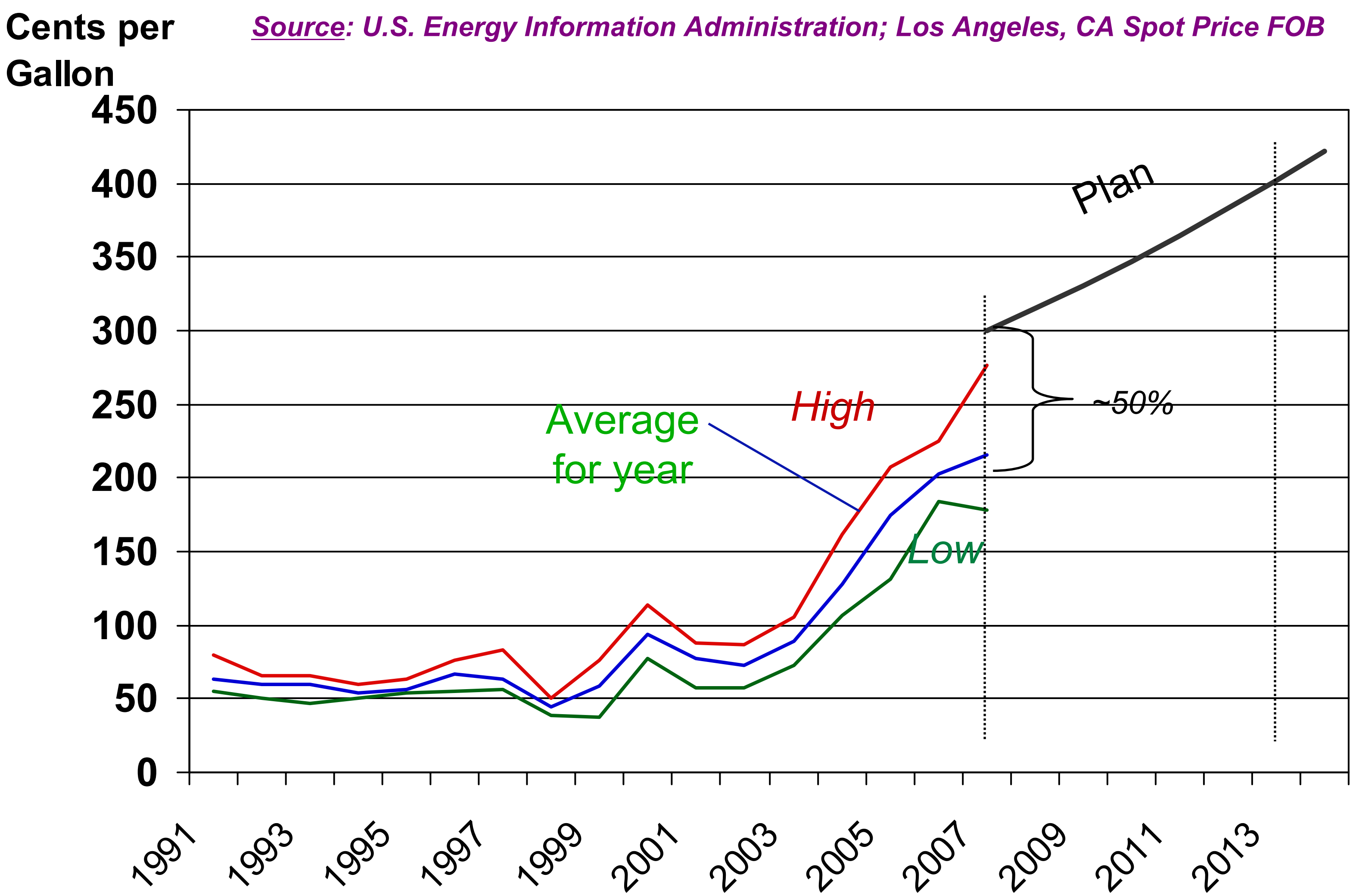
Annual Fuel Costs for Full SOFIA Operations

- ***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

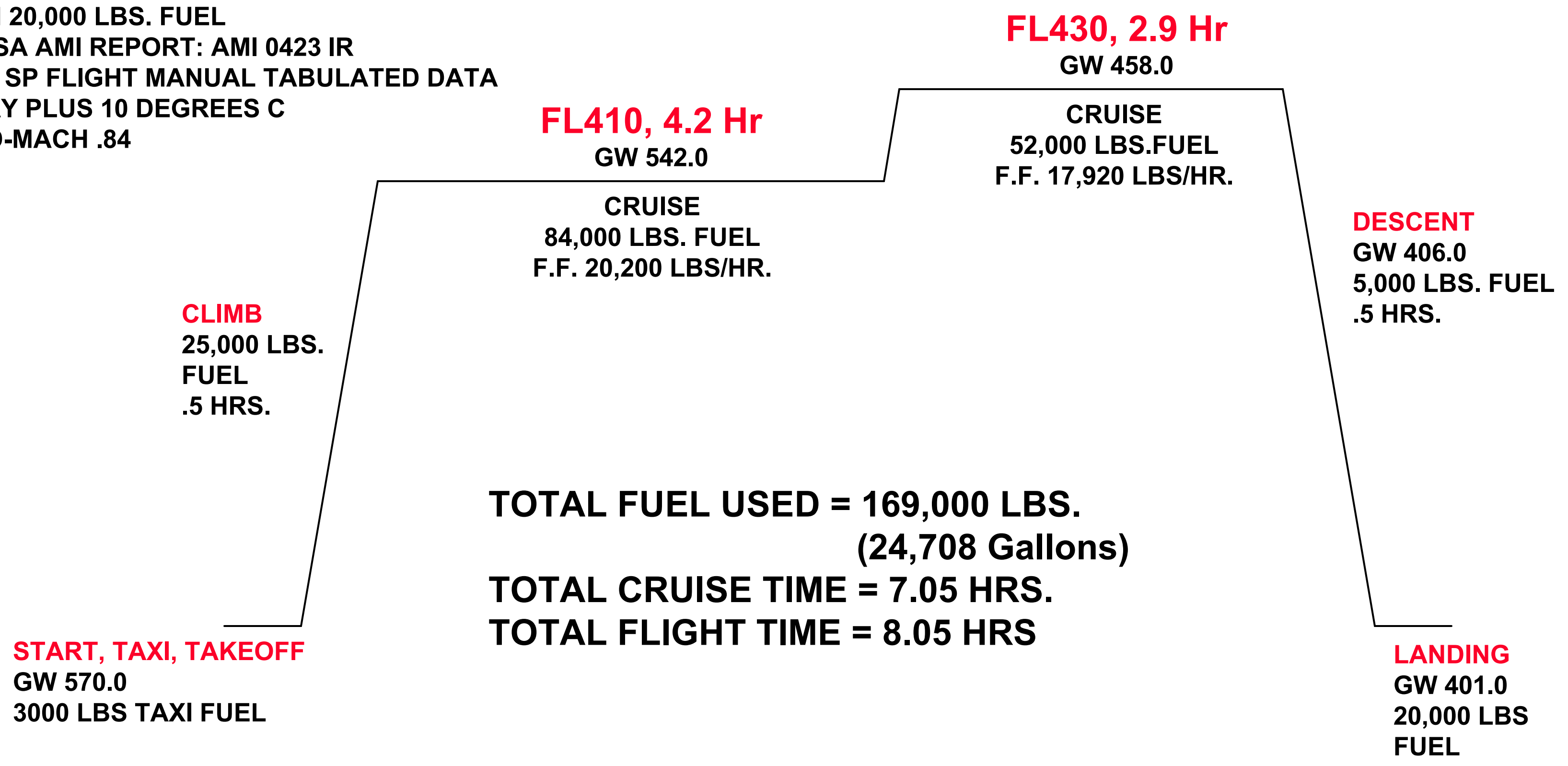


Flight Profile 1

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

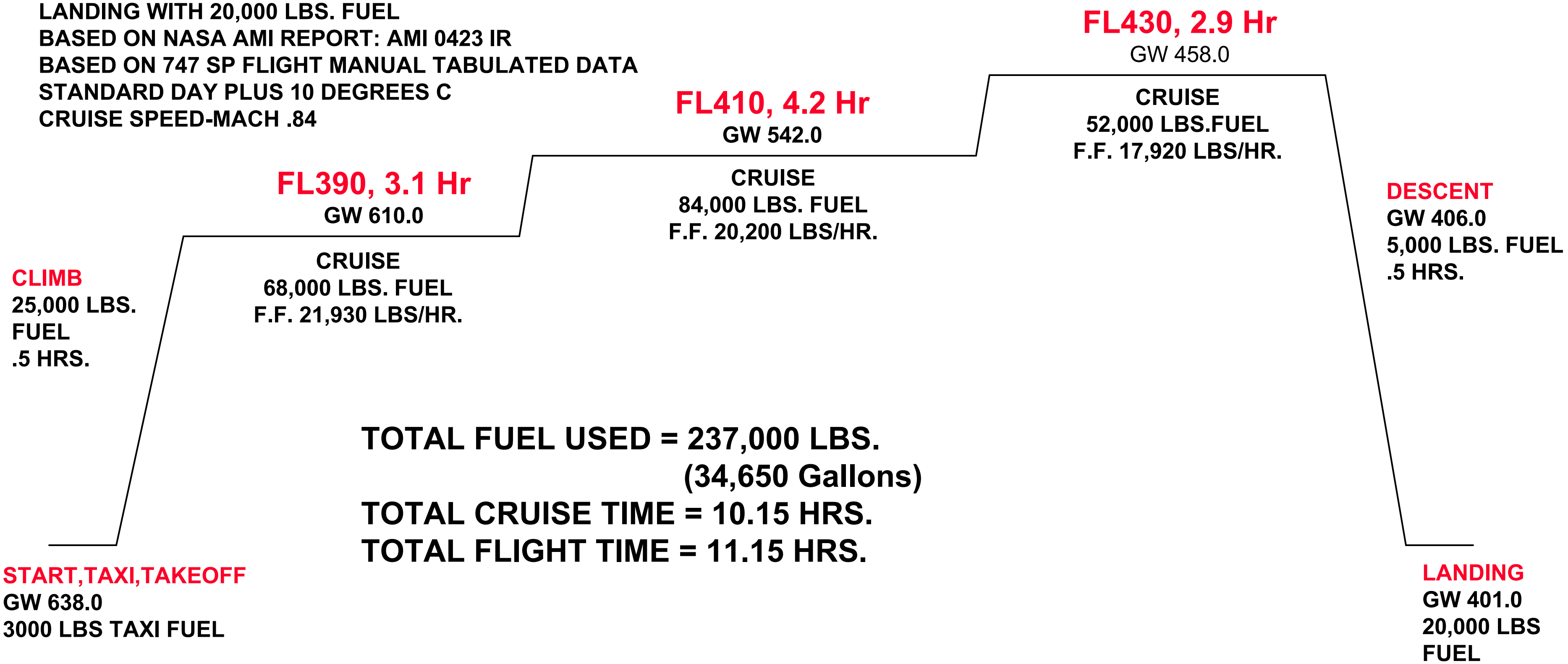


Flight Profile 2

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



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

Gören 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***