The Stratospheric Observatory for Infrared Astronomy (SOFIA)

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This talk will be posted at http://www.sofia.usra.edu/

Goddard Space Flight Center, February 25, 2011

R. D. Gehrz
Outline

• SOFIA Heritage and Context
• SOFIA Aircraft and Observatory Development Program
• SOFIA Performance Specifications
• SOFIA Science
• SOFIA Science and Instrumentation Schedule
• Summary
The History of Flying Infrared Observatories

1967
NASA Lear Jet Observatory

1974
NASA Kuiper Airborne Observatory (KAO)

2009
NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)

1983
NASA Infrared Astronomical Satellite (IRAS)

1995
ESA Infrared Space Observatory (ISO)

2003
NASA Spitzer Space Telescope

Science objectives
SOFIA Mission Overview, Aircraft Modification, and Status as of February 25, 2011
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 Science 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: Selecting the Aircraft

- Fuselage diameter (length not an issue)
- Payload and loiter time at FL >410
- Cost ($13M in 1995 dollars)

The winner:
Boeing 747-SP
Retrofitted with P&W JT9D-7J engines to provide operational margin
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
Observers in pressurized cabin have ready access to the focal plane

Pressure bulkhead

Spherical Hydraulic Bearing

Nasmyth tube

f/19.6 Focal Plane

Primary Mirror M1

M2

M3-1

M3-2

Focal Plane Imager

Nasmyth: Optical Layout
Telescope Size is Maximum that can fit Available Volume
BASELINE FINITE ELEMENT MODEL

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FEM Predictions for Unmodified Aircraft
FEM Validation: Pre-Modification Flight Test Data

Sample Longitudinal Strain - Positive Vertical Acceleration

FEM Predicted Longitudinal Strain and Flight Test Calibrated Strain vs. Water Line
FEM Station 1990 (LHS)

Microstrain, uin/in
Modified Baseline Finite Element Model
Frame Modifications and Sill Beams

Incremental Critical Design Review = ICDR
Control Cables - SOFIA Routing

Pitot Lines 96128400
Flight Control Cables 96128500
Hydraulic Lines (left side) 96128300
APU Fuel Line 96128210

FWD
Door System Fairings

- Aft Fairing
- Forward Fairing
- Lower Fairing
- Fiberglass Close-out
- Fiberglass Close-out
Studies of Cavity Acoustics: SOFIA 7% model in Ames 14 foot Transonic Wind Tunnel
7% Wind Tunnel Tests

Test Description/Conditions

- Boeing 747-SP 7% Model
- NASA ARC 14-Foot Tunnel
- Mach: $0.3 < M < 0.92$
- Yaw: $-4.5 < b < 4.5^\circ$
- Angle of attack: $2^\circ < a < 5^\circ$
- TA Elevation: $25^\circ < g < 60^\circ$

Data Acquired /Design validation

- Aero-acoustics
- Telescope torque
- Pressure loads
- Boundary layer characterization

Partial External Door
Dynamic Environment in the Cavity

Shear Layer at Cavity Opening

Standing Waves Excited by the Shear Layer

Wind in Cavity Induced by the Shear Layer

Aircraft Vibrations

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Stability and Control Studies: SOFIA Model in U of W Kirsten Wind Tunnel
Telescope inside Aircraft Cavity
SOFIA Airborne with Door Open!

NASA's Stratospheric Observatory for Infrared Astronomy 747SP on Dec. 18, 2009. (NASA Photo / Carla Thomas)
SOFIA Science
SOFIA Science: Studying the Chemical Evolution of the Universe
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
The Seven First Generation SOFIA Science Instruments (SIs)

Early Science SIs

- FIFI LS
- EXES
- HIPO
- FLITECAM w/ grisms
- FORCAST w/ grisms
- FORCAST
- GREAT
- HAWC

SOFIA First Generation Spectroscopy
The Eight First Generation SOFIA Science Instruments (SIs)
Photometric Sensitivity and Angular resolution

SOFIA is as sensitive as ISO

SOFIA is diffraction limited beyond 25 μm (θ_{min} ~ λ/10 in arcseconds) and can produce images three times sharper than those made by Spitzer.
The First Light and Early Science with FORCAST

The FORCAST Team in action during the First Light Flight

The FORCAST Team
First Light on May 26, 2011 UT: We demonstrated imaging capability from 5 to 37 microns with 3-4 arcsecond FWHM

Red = 37.1 µm, Green = 24.2 µm, Blue = 5.4 µm
SOFIA’s FORCAST First-Light Images: M82

M82

May 26, 2010 UT

Inset (visible light)

Visible light image

SOFIA infrared image (19.7, 31.5, and 37.1 μm)
PSF and Jitter from Images of γ Cygni

2,800 2.5 ms images shifted and co-added

Same data w/o shift and add

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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
SOFIA Early Science Images

visible light (HST)  near-infrared (ESO)  mid-infrared (SOFIA)
SOFIA Early Science Images

Red = 20 µm
Green = 12 µm
Blue = 11 µm

Wyoming Infrared Image from Herzog et al., 1980, Sky and Telescope, 59, 18

Red = 37.1 µm, Green = 24.2 µm

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GREAT Early Science in April 2011
Thermal Emission from ISM Gas and Dust

- 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.

Spectral Energy Distribution (SED) of the entire LMC (courtesy of F. Galliano)
The Physics and Chemistry of Protoplanetary Disks

- High spectral resolution enables dynamical studies and can establish where different atomic, molecular, and solid state species reside in the disk

- Small stellar-centric radii are associated with wide, double-peaked line profiles; large radii with narrow line profiles

- Observing many disks of different ages will trace the temporal evolution of disk dynamics and chemistry

Simulations from N. J. Evans et al. 2009
Observing Comets in the IR with SOFIA

- Comet nuclei are the “Rosetta Stone” of the Solar System

- 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 thermal 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?

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

The vertical lines mark features of crystalline Mg-rich crystalline olivine (forsterite)
SOFIA and Comets: Gas Phase Constituents

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

- Production rates of water and other volatiles
- Water $\text{H}_2$ 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 $\text{CH}_4$
- 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?


- 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.
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

Occultations: Rings and Moons

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

- There are 358 extra-solar planets; more than 59 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

Transits provide good estimates for the mass, size and density of the planet
- Transits can reveal the presence of satellites, and/or planetary rings
- Spectroscopic observations can reveal the presence and composition of an atmosphere

HD 209458b transit:
- a) artist’s concept and
- b) HST STIS data
Detection of Biogenic Molecules in Extrasolar Planetary Atmospheres by the transit Method

M. R. Swain et al.

HD 189733b

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SOFIA Will Study the Diversity of Stardust

- 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
SOFIA and Classical Nova Explosions

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

Spitzer Spectra of Nova V382 Vel


- 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?

- 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

US Basic Science Program

12 Flights available (3 additional flights being negotiated)

• Call for Proposals released April 2010
• 60 unique proposals were received
  – 53 with US PIs (26 Institutions)
  – 7 with International PIs (5 Institutions)
• 49 FORCAST Proposals and 11 GREAT Proposals
• Requested Time
  – 234 hours requested for FORCAST
  – 42 hours requested for GREAT
## FORCAST US Basic Science Awards

<table>
<thead>
<tr>
<th>PI</th>
<th>Institution</th>
<th>Title</th>
<th>Country</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tan</td>
<td>U Florida</td>
<td>Peering to the Heart of Massive Star Birth</td>
<td>US</td>
<td>4.5</td>
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<tr>
<td>Rubin</td>
<td>NASA/ARC</td>
<td>SOFIA’s Opportunity to Solve the Nebular Abundance Problem</td>
<td>US</td>
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<tr>
<td>Rebull</td>
<td>JPL</td>
<td>SOFIA Observations of the Gulf of Mexico Cluster</td>
<td>US</td>
<td>2.5</td>
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<tr>
<td>Werner</td>
<td>JPL</td>
<td>FORCAST Imaging of Planetary Nebulae</td>
<td>US</td>
<td>4.0</td>
</tr>
<tr>
<td>Shuping</td>
<td>USRA</td>
<td>Mid-Infrared imaging of the W40 Star Forming Region using SOFIA-FORCAST</td>
<td>US</td>
<td>1.5</td>
</tr>
<tr>
<td>Looney</td>
<td>U. Illinois</td>
<td>Resolving Class 0 Binaries in the Mid-Infrared</td>
<td>US</td>
<td>4.0</td>
</tr>
<tr>
<td>Grady</td>
<td>Eureka Scientific</td>
<td>Spatially-Resolved Far-Infrared Imaging of Bright Debris Disks</td>
<td>US</td>
<td>2.7</td>
</tr>
<tr>
<td>Sarre</td>
<td>U. Nottingham</td>
<td>FORCAST Study of 21 Micron Sources</td>
<td>UK</td>
<td>0.6</td>
</tr>
<tr>
<td>Harvey</td>
<td>U Texas</td>
<td>Far-IR Interferometry With SOFIA: A Test of Lunar Occultation Observations</td>
<td>US</td>
<td>0.4</td>
</tr>
<tr>
<td>Bally</td>
<td>U. Colorado</td>
<td>FORCAST imaging of the mini-starburst in W43</td>
<td>US</td>
<td>5.0</td>
</tr>
<tr>
<td>Armus</td>
<td>IPAC</td>
<td>Observations of the Nearby Starburst Galaxy NGC 2146 with FORCAST on SOFIA</td>
<td>US</td>
<td>2.8</td>
</tr>
<tr>
<td>Hill</td>
<td>CEA Saclay</td>
<td>SOFIA 24 and 35um imaging of the OB young stellar objects in Cygnus-X</td>
<td>France</td>
<td>2.8</td>
</tr>
<tr>
<td>Vacca</td>
<td>USRA</td>
<td>Uncovering Buried Star Clusters in Nearby Starburst Galaxies</td>
<td>US</td>
<td>3.0</td>
</tr>
<tr>
<td>Huard</td>
<td>UMD College Park</td>
<td>Resolving Protostars in the Serpens South Protocluster</td>
<td>US</td>
<td>2.1</td>
</tr>
<tr>
<td>Nikola</td>
<td>Cornell</td>
<td>Probing The AGN-Starburst Connection</td>
<td>US</td>
<td>2.0</td>
</tr>
<tr>
<td>Sandell</td>
<td>USRA</td>
<td>The nature of Young High-mass (proto)stars in NGC7538</td>
<td>US</td>
<td>3.4</td>
</tr>
<tr>
<td>Rushton</td>
<td>U Central Lancashire</td>
<td>SOFIA observations of recurrent novae</td>
<td>UK</td>
<td>2.0</td>
</tr>
<tr>
<td>Meixner</td>
<td>STSci</td>
<td>FORCASTing Evolved Star Mass Loss in the Galactic Bulge</td>
<td>US</td>
<td>2.0</td>
</tr>
<tr>
<td>Humphreys</td>
<td>U. Minnesota</td>
<td>Cool Dust and the Mass Loss Histories of Cool Hypergiants</td>
<td>US</td>
<td>2.0</td>
</tr>
<tr>
<td>Orton</td>
<td>JPL</td>
<td>19–37 Micron Photometry of Outer Planets</td>
<td>US</td>
<td>1.2</td>
</tr>
</tbody>
</table>

52.1

http://sofia.usra.edu/Science/
# GREAT US Basic Science Awards

<table>
<thead>
<tr>
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<th>Country</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sahai</td>
<td>JPL</td>
<td>Using GREAT to Probe [CII] emission in the Ring Nebula</td>
<td>US</td>
<td>3.2</td>
</tr>
<tr>
<td>Neufeld</td>
<td>JHU</td>
<td>Search for interstellar mercapto radicals (SH) with SOFIA</td>
<td>US</td>
<td>3.0</td>
</tr>
<tr>
<td>Kaufman</td>
<td>CalState SJ</td>
<td>High frequency water masers with SOFIA/GREAT</td>
<td>US</td>
<td>3.0</td>
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<tr>
<td>Schneider</td>
<td>CEA Saclay</td>
<td>Pillars of Creation: physical origin and connection to star formation</td>
<td>France</td>
<td>2.4</td>
</tr>
<tr>
<td>Hewitt</td>
<td>GSFC</td>
<td>GREAT Diagnostics of Molecular Shocks in Interacting Supernova Remnants</td>
<td>US</td>
<td>1.0</td>
</tr>
<tr>
<td>Li</td>
<td>JPL</td>
<td>Mapping &quot;Dark Gas&quot; in Rho Ophiuchus A</td>
<td>US</td>
<td>4.8</td>
</tr>
</tbody>
</table>

http://sofia.usra.edu/Science/
Anticipated Science Schedule

- **April 2011**    GREAT Early Science Flights
- **May – June 2011**   FORCAST Basic Science Flights
- **June 2011**   Observatory Engineering Flights
- **July – September 2011**   GREAT Early Science
- **Late 2011**   Next Call for GI Science Proposals
Future Instrumentation Development

• Draft solicitation released on December 15, 2010
• First Solicitation release: Mid 2011 (target)
• Proposals due 90 days later
• Selections announced: Late 2011
• Contracts initiated: Early 2012
• There will be additional calls every three years
• $5-$10 million/year for life of the program
Summary

- The Program is making progress!
  - Flight envelope testing is completed
  - Science flights have begun

- 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 Terahertz Frequencies
- FIFI-LS: Field Imaging Far-Infrared Line Spectrometer
- HAWC: High-resolution Airborne Wideband Camera
- EXES: Echelon-Cross -Echelle Spectrograph
## SOFIA’s First-Generation Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Type</th>
<th>$\lambda$ ((\mu)m)</th>
<th>Resolution</th>
<th>PI</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIPO (Available 2010)</td>
<td>fast imager</td>
<td>0.3 - 1.1</td>
<td>filters</td>
<td>E. Dunham</td>
<td>Lowell Obs.</td>
</tr>
<tr>
<td>FLITECAM * (Available 2010)</td>
<td>imager/grism</td>
<td>1.0 - 5.5</td>
<td>filters/R~2000</td>
<td>I. McLean</td>
<td>UCLA</td>
</tr>
</tbody>
</table>
| GREAT (Available 2009) | heterodyne receiver | 62 - 65  
111 - 12  
158 - 187  
200 - 240  | R ~ $10^4$ - $10^6$ | R. Güsten    | MPIfR            |
| FIFI LS ** (Available 2009) | imaging grating spectrograph | 42 - 110,  
110 - 210  | R ~1000 - 2000 | A. Poglitsch | MPE               |

* Facility-class instrument  
** Developed as a PI-class instrument, but will be converted to Facility-class during operations
Continuum Sensitivities
(10σ in 900 sec on source time)

MDCF (Jy)

λ (μm)

FLITECAM imaging
EXES High R
EXES Low R
FORCAST [R=40 filter]
FIFI-LS Blue channel order2
FIFI-LS Blue channel order1
FIFI-LS Red channel
HAWC

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Line Sensitivities with Spectrometers

(10σ in 900 sec on source time)
**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

**FL390, 3.1 Hr**
GW 610.0

- CRUISE
  - 68,000 LBS. FUEL
  - F.F. 21,930 LBS/HR.

**FL410, 4.2 Hr**
GW 542.0

- CRUISE
  - 84,000 LBS. FUEL
  - F.F. 20,200 LBS/HR.

**FL430, 2.9 Hr**
GW 458.0

- CRUISE
  - 52,000 LBS. FUEL
  - F.F. 17,920 LBS/HR.

**DESCENT**
GW 406.0

- 5,000 LBS. FUEL
- .5 HRS.

**LANDING**
GW 401.0

- 20,000 LBS FUEL

**TOTAL FUEL USED = 237,000 LBS.**
(34,650 Gallons)

**TOTAL CRUISE TIME = 10.15 HRS.**

**TOTAL FLIGHT TIME = 11.15 HRS.**

**START, TAXI, TAKEOFF**
GW 638.0
3000 LBS TAXI FUEL
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

START, TAXI, TAKEOFF
GW 570.0
3000 LBS TAXI FUEL

FL410, 4.2 Hr
GW 542.0
CRUISE
84,000 LBS. FUEL
F.F. 20,200 LBS/HR.

FL430, 2.9 Hr
GW 458.0
CRUISE
52,000 LBS. FUEL
F.F. 17,920 LBS/HR.

DESCENT
GW 406.0
5,000 LBS. FUEL
.5 HRS.

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

LANDING
GW 401.0
20,000 LBS FUEL
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
