Recent Science Results from The Stratospheric Observatory for Infrared Astronomy (SOFIA)

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This talk is at: http://www.sofia.usra.edu/Science/speakers/index.html

University of Wyoming, Laramie, Wyoming, November 9, 2012
Outline

- The SOFIA Facility and its Status
- SOFIA Science Instrumentation/Performance Specifications
- Early SOFIA Science Results
- SOFIA Schedule and General Investigator (GI) Opportunities
- Summary
SOFIA Overview

• **2.5 m telescope in a modified Boeing 747SP aircraft**
  – Imaging and spectroscopy from 0.3 $\mu$m to 1.6 mm
  – Emphasizes the obscured IR (30-300 $\mu$m)

• **Operational Altitude**
  – 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 images were obtained on May 26, 2010
  – 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 SOFIA Observing Environment

- Above 99.8% of the water vapor
- Transmission at 14 km >80% from 1 to 800 µm
- Emphasis is on the obscured IR regions from 30 to 300 µm

SOFIA, 10 µm Precipitable Water Vapor

Cerro Chajnantor, 700 µm Precipitable Water Vapor


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The SOFIA Observatory


Door
**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
SOFIA: Modeling the Aircraft

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

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Modified Baseline Finite Element Model
New 21.3 foot diameter Pressure Bulkhead

Bulkhead simulator used in Germany for Telescope Assembly buildup

FEM

Bulkhead on Delivery
Frame Modifications and Sill Beams
Control Cables - SOFIA Re-routing

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

FWD
Control Cable Re-routing Details

BP#1

BP#2

STA1394

Forward Bulkhead Plate

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Door System Fairings
SOFIA Door System
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: \(0.3 \leq M \leq 0.92\)
- Yaw: \(-4.5 \leq \beta \leq 4.5^\circ\)
- Angle of attack: \(2^\circ \leq \alpha \leq 5^\circ\)
- TA Elevation: \(25^\circ \leq \gamma \leq 60^\circ\)

Data Acquired /Design validation

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

Partial External Door

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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
Stability and Control Studies: SOFIA Model in U of W Kirsten Wind Tunnel
Telescope and Optical Layout

Telescope Size is Maximum for Available Volume
Major Telescope Components

Science Instrument

Counter Weight

Hydraulic System Motors

Forward Bulkhead

Cameras

Focal Plane Imager

Vibration Isolation

Primary Mirror M1

M2

M3-1

M3-2
Back End of the SOFIA Telescope
SOFIA Airborne on July 13, 2010

First Door Open Flight  
Door Open 100
SOFIA Science Instruments

SOFIA supports a unique, expandable suite of Science Instruments (SIs)

- SIs cover the full IR range with imagers and low to high resolution spectrographs
- 4 SIs at Initial Operations; 7 SIs at Full Operations.
- SOFIA will take advantage of improvements in instrument technology.
- Will support both Facility Instruments and PI Class Instruments
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
Results from the First Round of SOFIA Flights
First Science Results with FORCAST

The DSI Telescope Assembly and Mission Operations Team in action during the First Light Flight

The FORCAST Team

Eight papers have been published in ApJ Letters, 749, L17 (April 20 2012)
First Light on May 26, 2010 UT: We demonstrated diffraction limited imaging capability at 30 microns

Red = 37.1 μm, Green = 24.2 μm, Blue = 5.4 μm

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SOFIA Image Quality During Early Science

Average Measured IQ (Early Science Flight on 2010-11-19)

Diffraction + 1.4” RMS Pointing Stability

Diffraction + 0.5” RMS Pointing Stability

Diffraction Limit

FWHM (arcsec)

Wavelength (microns)

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May 5, 2011: First Basic Science Flight
Inside the Observatory on the First Basic Science Flight

Telescope_Motion.wmv
20 (Green) and 37 (Red) Micron Data of Orion Nebula

Visible light
(HST, C. O'Dell and S. Wong)

Near infrared
(ESO, M. McCaughrean)

SOFIA mid infrared
(SS02)
SOFIA FORCAST Images of the Orion Nebula

Red = 37.1 μm, Green = 24.2 μm

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

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

KAO 38 um

BN/KL Region
Blue=19um Green=31um Red=37um

Background Image: Spitzer

BN
IRc2
Source I
IRc3
IRc4

De Buizer et al. (2012)

(Stacey et al. 1995)

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BN declines in prominence at longer l’s

IRc4 dominates at l >31um

A previously unidentified area of emission is apparent at l >31um (SOF1)
• **IRc4 luminosity is too high to be caused by external heating**

• **BN+IRc4 account for ~50% of the ~10^5 L☉ of the BN/KL region**
First Science Results with GREAT on SOFIA

Twenty two papers on GREAT science have been published in a special edition of A & A Letters (2012, Volume 542)

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Early Science with GREAT (White CII, Green CO)

- GREAT maps M17 SW molecular cloud
- CII traces the photo-dissociation region created on the surface of the dark cloud by the ionizing radiation from the hot young stars
- CO traces the warm cores where star formation may be occurring
Studies of OH with GREAT on SOFIA

• The OH (hydroxyl) was the first interstellar molecule detected in absorption at 18 cm radio wavelengths (Weinreb et al. 1963, Nature, Vol. 200, 829)

• The hyperfine $\Lambda$ doublet at 18 cm wavelengths is well studied (both thermal and maser) from the ground, but this emission is dominated by relatively cool, diffuse gas ($N \sim 10^3 \text{ cm}^{-3}$)

• The FIR rotational lines of the OH $^2P_{1/2}$ and $^2P_{3/2}$ are observable with GREAT on SOFIA (the only facility that can do this) and probe denser, hotter gas than the 18 cm lines.
GREAT is tuned to observe the Λ doubling and hyperfine structure of the 163 μm (1.8378 THz and 1.8377 THz) and the 119 μm (2.514 THz) lines.

Fig. 1. Schematic representation of the lowest 28 energy levels of 16OH. The Λ doubling and hyperfine splitting are not shown to scale.
OH $^{2}\Pi_{3/2}$ $J = 5/2 \leftarrow 3/2$ (119 µm)

- Wiesemeyer et al. (2012, A&A, 542, L7) observed the 119 µm OH ground state line in absorption towards several ultra compact HII regions.

- This is the first astrophysical velocity resolved spectrum ever observed of this transition.

- The line traces molecular gas in the spiral arm clouds along the line of sight and near the HII regions.

- Using Herschel observations of H$_2$O, they find that the H$_2$O to OH abundances ranges from 0.3 – 1.0.
$\text{OH}^2\Pi_{1/2}, J = 3/2-1/2$ (163 $\mu$m)

- Csengeri et al (2012, A&A, 542, L8) observed the $J = 3/2 - 1/2$ rotational OH transition in emission towards several ultra compact HII/OH maser sources. One pair (blue) in the signal band and the other fortuitously in the image side band (red)

- These observations show that the observed line intensities require a compact, high OH column density, warm gas component
Discovery of SH (Mercapto radicals) in Interstellar Space

- **SH** is one of the simplest Hydrides previously undetected in the ISM

- Its ground state rotation line at 1.383 THz (217 microns) shows Lambda-type doubling (nuclear rotation-electron spin interaction), so it is easy to identify

- W49N intersects several molecular clouds in its own and another spiral arm that cause absorption of the continuum.
Mercapto Radicals in Absorption Toward W49N

• Hydrogen Sulfide ($H_2S$) is seen in absorption at the same velocities
• The implied diffuse cloud abundance ratio, $SH/H_2 \sim 10^{-8}$, suggests the presence of elevated gas temperatures ($\sim 1000K$) within cloud cores

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Probing Protostellar In-Fall with Terahertz Ammonia Absorption in an Ultra Compact HII Region

- Red-shifted ammonia ($\text{NH}_3$) absorption due to infall detected against the optically thick dust continuum
- Optically thin $^{17}\text{C}^{17}\text{O}$ at 1.27 cm (23.7 GHz) gives the systemic velocity
Detection of OD Absorption towards the Low-mass Protostar IRAS 16293-2422

- Detection of the OD ground state line at 1.39 THz (216 μm) is detected in absorption

- First detection of OD outside of the solar system.

- The OD/HDO abundance of 17-90 where the absorption takes place is high compared to model values

- Dissociative recombination of $\text{H}_2\text{DO}^+$ into OH and $\text{H}_2\text{O}$ may cause HDO depletion
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.
HIPO/FDC Observation of Stellar Occultation by Pluto

Scientific goals

• Measure temperature profile of Pluto’s atmosphere
• Test atmospheric freeze-out models
• Target central flash – global atmospheric shape, possible extinction

Programmatic Goal

• Demonstrate successful in-flight prediction update and flight plan change to enable observation on the central chord

Ted Dunham et.al. (HIPO), Lowell Observatory, Jürgen Wolf (SOFIA DSI) & Mike Person et al., MIT
Pluto Occultation Results

- Central brightening seen in HIPO blue and red channels and Fast Diagnostic Camera (FDC) visual channel
- Post-event data indicates impact parameter < 100 km!
- The atmosphere of Pluto is still there contrary to predictions that it will frozen out as Pluto heads for aphelion
- Central brightening suggests the presence of a low-altitude haze layer
Science Schedule

- Aircraft and telescope control improvements are underway. Test flights will resume in November, 2012.

- The Cycle 1 science call resulted in the award of about 200 hours of community science. There will be ~45 flights including ~8 Southern Hemisphere flights.

- Cycle 1 observations will begin with GREAT observations in November, 2012. New SIs are HIPO, FLITECAM, and FORCAST/FLITECAM GRISMs.

- Cycle 2 proposals will be called for in Spring 2013 and due in June, 2013. EXES and FIFI-LS will be added as SIs.

- There will be additional science calls annually.
Future Instrumentation Development

- A call for SOFIA second generations SIs was released on July 17, 2011
- Eleven proposals were ingested on October 7, 2011
- The selection of two proposals for upgrades to HAWC was announced on April 17, 2012.
  - A new detector will increase the number of pixels from 380 to 2400
  - A wide-field polarimetric capability will be added
- NASA plans to issue another SI AO in 2014
Summary

• The Program is making progress!
  ➢ Early and Basic Science flights have been concluded and have produced interesting results and 30 publications
  ➢ Pluto occultation observation showcases SOFIA’s potential
  ➢ Performance expectations are being met
  ➢ Cycle 1 observations will begin in 6 months

• SOFIA will be one of the primary observational facilities for far-IR and submillimeter astronomy for many years

Our Web site: http://www.sofia.usra.edu/

This talk: http://www.sofia.usra.edu/Science/speakers/index.html

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Backup
# Future Molecular Spectroscopy with SOFIA

<table>
<thead>
<tr>
<th>Name</th>
<th>Spectroscopic Capability</th>
<th>PI</th>
<th>Institution (Year of Commissioning)</th>
<th>Wavelengths (µm)</th>
<th>Spectral Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>FORCAST</td>
<td>Grism Spectrometer</td>
<td>T. Herter</td>
<td>Cornell (2013)</td>
<td>5-40</td>
<td>200</td>
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<tr>
<td>GREAT</td>
<td>Heterodyne Spectrometer</td>
<td>R. Güsten</td>
<td>MPIfR (2011-13)</td>
<td>60-240</td>
<td>10⁶-10⁸</td>
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<tr>
<td>FLITECAM</td>
<td>Grism Spectrometer</td>
<td>I. McLean</td>
<td>UCLA (2013)</td>
<td>1-5</td>
<td>2000</td>
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<tr>
<td>EXES</td>
<td>Mid-Infrared Spectrometer</td>
<td>M. Richter</td>
<td>UC Davis (2014)</td>
<td>5-28</td>
<td>3000, 10⁴, 10⁵</td>
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</table>
## SOFIA’s First-Generation Instruments

(\url{http://www.sofia.usra.edu/Science/instruments/})

see also Gehrz et al. 2011 (arXiV:1102.1050)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Type</th>
<th>$\lambda$ (µm)</th>
<th>$\nu$ (THz)</th>
<th>Resolution</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>FORCAST</td>
<td>imager / (grism)</td>
<td>5.4 - 37</td>
<td>8.1 - 56</td>
<td>filters / (R~2000)</td>
<td>T. Herter / Cornell U.</td>
</tr>
<tr>
<td>(in operation)</td>
<td></td>
<td></td>
<td></td>
<td>R \sim 10^4 - 10^8</td>
<td>R. Güsten / MPIfR</td>
</tr>
<tr>
<td>GREAT</td>
<td>heterodyne spectrometer</td>
<td>(62 - 65)</td>
<td>(4.6 - 4.8)</td>
<td>R \sim 10^4 - 10^8</td>
<td>R. Güsten / MPIfR</td>
</tr>
<tr>
<td>(H-Freq.)</td>
<td></td>
<td>(110 - 125)</td>
<td>(2.4 - 2.7)</td>
<td></td>
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<tr>
<td>(M-freq. -- June 2011)</td>
<td></td>
<td>156 - 165</td>
<td>1.82 - 1.92</td>
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<tr>
<td>(L-freq.'s -- operating)</td>
<td></td>
<td>200 - 240</td>
<td>1.25 - 1.50</td>
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<tr>
<td>HIPO</td>
<td>fast imager</td>
<td>0.3 - 1.1</td>
<td></td>
<td>filters</td>
<td>E. Dunham / Lowell Obs.</td>
</tr>
<tr>
<td>(summer 2011)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLITECAM</td>
<td>imager / (grism)</td>
<td>1.0 - 5.5</td>
<td></td>
<td>filters / (R~2000)</td>
<td>I. McLean / UCLA</td>
</tr>
<tr>
<td>(summer 2011)</td>
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<tr>
<td>FIFI-LS</td>
<td>imaging grating spectrograph</td>
<td>42 - 110</td>
<td>2.7 - 7.1</td>
<td>R \sim 1000 - 2000</td>
<td>Poglitsch,Krabbe /MPE,IRS</td>
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<tr>
<td></td>
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<td>110 - 210</td>
<td>1.4 - 2.7</td>
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<tr>
<td>EXES</td>
<td>imaging echelle spectrograph</td>
<td>4.5 - 28.4</td>
<td>10.6 - 67</td>
<td>R \sim 3000 - 10^5</td>
<td>M. Richter / UC-Davis</td>
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<tr>
<td>HAWC</td>
<td>imager</td>
<td>45 - 270</td>
<td>1.1 - 6.6</td>
<td>filters</td>
<td>D. A. Harper / U. Chicago</td>
</tr>
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</table>
SOFIA and Comets during Perihelion Passage

What can SOFIA tell us about the origin of the Solar System for studies of comets at perihelion passage?

- Comet dust mineralogy and physical properties
- Comparisons with IDPs
- Comparisons with meteorites
- Comparisons with Stardust
- Only SOFIA can get these observations

SOFIA and Classical Nova Explosions

What can SOFIA tell us about Classical Nova Explosions?

- Gas phase abundances
- Stardust formation and mineralogy, and abundances
- Contributions to ISM clouds
- Kinematics of the Ejection

Spitzer Spectra of Nova V382 Vel

EXES: 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
**EXES and Comets: Gas Phase Constituents**

- **Production rates of water and other volatiles**
- **Water (H₂O) H₂ ortho/para (parallel – anti-parallel) hydrogen spin isomer ratio gives the water formation temperature; a similar analysis can done on the spin isomers of methane (CH₄)**
- **Only SOFIA can make these observations near perihelion**

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C/2003 K4 Spitzer

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67th International Symposium on Molecular Spectroscopy, Columbus, OH, June 21, 2012