The Stratospheric Observatory for Infrared Astronomy (SOFIA)

by

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SPIE Astronomical Instrumentation, Marseille, France, June 27, 2008

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Outline

- SOFIA Heritage and Context
- SOFIA Facility Status Report
- SOFIA’s Science Capabilities
- Research with SOFIA
- SOFIA Schedule
- Opportunities for International Collaboration on SOFIA
- Summary
SOFIA’s Heritage and Context
The History of Air and Space Infrared Astronomy

1967

NASA Lear Jet Observatory

1974

NASA Kuiper Airborne Observatory (KAO)

1983

NASA Infrared Astronomical Satellite (IRAS)

1995

ESA Infrared Space Observatory (ISO)

2003

NASA Spitzer Space Telescope

2009

NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)
SOFIA and its Companions in Space

SIRTF 2003

HERSHCEL 2008/9

SOFIA 2009

JWST 2013

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SOFIA and Major IR Imaging/Spectroscopic Space Observatories

Ground-based Observatories

SOFIA

SPICA

Herschel

Warm Spitzer

SPITZER

AKARI

JWST

SAFIR

Wavelength (µm)

Frequency (THz)

2005  2010  2015  2020  2025

0.3

3

30

100

10

1

1000
SOFIA and Herschel: Complementarity, Synergism

- 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 Status Report
SOFIA Overview

• 2.5 m telescope in a modified Boeing 747SP aircraft
  – 0.5 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
  – 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
Layout of Personnel and Accomodations
(upper deck not shown)

Mission Control & Science Operations Section

Education & Public Outreach Section

Pressure Bulkhead

Open Port Telescope Cavity

Cavity Environmental Control System

Science Instrument

Telescope, 2.5 meter

Testdoor.mpg
Nasmyth: Optical Layout

- Pressure bulkhead
- Spherical Hydraulic Bearing
- Nasmyth tube
- Focal Plane
- Focal Plane Imager
- Primary Mirror
- M1
- M2
- M3-1
- M3-2
The Un-Aluminized Primary Mirror Installed
SOFIA Airborne!

26 April 2007, L-3 Communications, Waco Texas: SOFIA takes to the air for its first test flight after completion of modifications.
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

Successful lab demonstration of GREAT in July 2005
SOFIA Science Capabilities
SOFIA’s Unique Science Capabilities

- SOFIA is diffraction limited beyond 25 μm ($\theta_{\text{min}} \sim \lambda/10$ in arcseconds) and can produce images three times sharper than those made by Spitzer.
- SOFIA’s large aperture enables high resolution spectroscopy ($R = \frac{\lambda}{\Delta\lambda} = 10^3 - 10^8$).
- SOFIA’s 8 arcmin diameter FOV allows use of very large detector arrays.
- Large aperture and better detectors give SOFIA sensitivity for imaging and spectroscopy similar to that of space observatory ISO.
- SOFIA can respond rapidly to temporal events and track them.
- SOFIA can adapt to new technologies.
SOFIA First Generation Spectroscopy

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Photometric Sensitivity

![Graph showing photometric sensitivity across different wavelengths (µm)]

- 1 Sigma, 1 hr, Flux Density (mJy)
- Wavelength (µm)
- SOFIA
- KAO
- IRAS
- ISO
- Herschel
- Spitzer
Angular Resolution
Research with SOFIA
SOFIA: Science For the Whole Community

Wavelength [µm]

Spectral resolution

Planetary Atmospheres
Chemistry of the cold ISM
Dynamics of collapsing protostars
Dynamics of the Galactic Center
Velocity structure and gas composition in disks and outflows of YSOs
Composition/dynamics/physics of the ISM in external galaxies
PAH & organic molecules
Nuclear synthesis in supernovae in nearby galaxies
Composition of interstellar grains
Debris Disk Structure
Luminosity and Morphology of Star Formation Galactic and Extra-Galactic Regions
KBOs, Planet Transits

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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?
SOFIA Science: Targets of Opportunity

- Bright Comets
- Eruptive variable stars
- Galactic and LMC/SMC classical novae
- Supernova in our galaxy or other nearby galaxies
- Eclipses and Occultations
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 and spectrometers will be able to observe protostellar condensations where they emit most of their energy with unprecedented spatial detail.

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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

SOFIA and Extra-solar Debris Disks

What can SOFIA tell us about debris 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
An occultation occurs when a solar system object passes between an observer and a star. The star acts like a tiny probe as it sets behind the planet’s limb.

SOFIA can fly anywhere on the Earth, allowing it to position itself under the shadow of an occulting object.
Occultation astronomy with SOFIA

How will SOFIA help determine the properties of Dwarf Planets in and small bodies in the Solar System?

- Occultation studies with SOFIA will probe the sizes, atmospheres, and possible satellites of newly discovered planet-like objects in the outer Solar system.

- The unique mobility of SOFIA opens up some hundred events per year for study compared to a handful for fixed ground and space-based observatories.

Pluto occultation lightcurve observed on the KAO (1988) probes the atmosphere
SOFIA and Extra-solar Planet Transits

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

- More than 200 extra-solar planets, some of which 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 may reveal the presence of, satellites, and/or planetary rings

HD 209458b transit:

a) artist’s concept and

b) HST STIS data
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

Cold Molecular Hydrogen using HD

How can SOFIA be used to study the cold molecular hydrogen abundance in the Galaxy using the 112 \( \mu m \) 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 \( \mu m \) ground-state rotational line

- A GREAT high resolution spectrometer study is possible given ISO detection
- 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

**Atmospheric transmission around the HD line at 40,000 feet**
**SOFIA and Activity in Galactic Nuclei**

*What can SOFIA see at the center of our Galaxy?*

- **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**

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

*SOFIA beams*

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**SOFIA and the Black Hole at the Galactic Center**

*How will SOFIA study the massive black hole at the Galactic Center?*

- **SOFIA imagers and spectrometers can resolve detailed structures in the circum-nuclear disk at the center of the Galaxy**

- **An objective of SOFIA science to understand the physical and dynamical properties of the material that feeds the massive black hole at the Galactic Center**

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Schedule
SOFIA Schedule (Major Milestones)

- **First Re-Flight**  Occurred April ‘07
- **Ten Closed Door Flights**  Finished Dec ‘07
- **Door Drive Delivered**  Spring ‘08
- **Mirror coated and ground tests**  Spring/Summer 08
- **Open Door Flights at Palmdale**  Fall ‘08
- **First Science**  ‘09
- **Next Instrument call**  ‘10
Early US General Observer Opportunities

- **First call Early Science proposals this year**
  - Early Short Science Aug ‘08 with PI’s
  - Early Basic Science Dec ‘08 GO’s

- **Early Short Science with FORCAST and GREAT**
  - Special call for participation with PI’s
  - Very limited flights (~3)
  - GO’s will not fly

- **Early Basic Science also with FORCAST and GREAT**
  - Longer period (~15 Flights)
  - More capabilities
  - Call will be for GO Science and GO participation
Early Science with SOFIA

- The aircraft has flown in April 2007 and is now at NASA Dryden FRC for flight certification tests
- Early Science is expected to occur in 2009
- Two instruments have been selected for Early Science
  - FORCAST: a US 5-40 $\mu$m imager
  - GREAT: a German heterodyne 60 to 200 $\mu$m Spectrometer
  - Both have been tested in the lab or on a telescope
Next Call For New Instruments

- The next call for instruments will be at First Science ~ FY ’10

- We are considering:
  - 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

- Approximate 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 are being installed during summer of ‘08
  – First science will be in early ’09

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

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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
- CASIMIR: CAtech 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

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

* Listed in approximate order of expected in-flight commissioning

% Operational (August 2004)

§ Uses non-commercial detector/receiver technology

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