A Science Vision for SOFIA
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Harold W Yorke
Director, SOFIA Science Mission Operations
Setting the Stage (1/3)

• For NASA’s space missions, Level 1 requirements are sacrosanct (NPR 7120.5E)
  – Level 1 requirements result from years of careful planning, balancing cost, schedule, risk, and science
  – Changes, when they occur, are generally pre-planned descopes to account for changes of costs, schedule, and/or risk
  – Scope increases are seldom allowed
    • Exception: Herschel-HIFI bands 6 & 7 (1.9 THz receivers)
    • At the time 1.9 THz receiver was at TRL 3-4
• Once launched, hardware upgrades of spacecraft or its instruments are not possible
  • Exception: Hubble Space Telescope
SOFIA is not a space mission

- Hardware repairs & updates are in principal possible on a relatively short time scale
- SOFIA can reinvent itself on a time scale of ~five years
- Pursuing validation and verification of SOFIA’s “Level 1” requirements over many years may not make scientific sense

SOFIA’s current Level 1 requirements are based on decade-old vision

- What was important then may not be important now
- Project needs to periodically revisit priorities
• Computer technology advances make existing SOFIA hardware obsolete
  – Repairs of aging electronic components severely hampered (searches on Ebay!?)
  – Loss of corporate knowledge as key personnel leave project
• SOFIA’s new instrumentation and observing modes create new demands on the observatory not envisioned a decade ago
  – E.g. MCCS redesign should be a high priority
  – Adding new instruments requires decommissioning old ones
Defining SOFIA’s New Vision

• Redefining SOFIA for the next two decades should be a science community effort
  – Input from SOFIA SMO Director and SOFIA Project Scientist is important, but should not be soul source
  – Getting input from community right before SOFIA’s Senior Review may be problematic and disruptive

• Current advisory structure is complex
  – SNOPAC (NASA)
  – SOFIA International Summit (NASA/DLR)
  – SOFIA Science Council (USRA)
  – SOFIA Users Group (USRA)
  – GSSWG (DLR)
  – SPOT (NASA)
Hal’s Vision for the future SOFIA

• Formulate the most important science accessible to SOFIA based on NASA’s vision => “Origins”

• Define how SOFIA can uniquely address this science or uniquely contribute important pieces in synergy with other observatories
  – SOFIA cannot be everything for everyone – it is not a general purpose observatory
  – Must make investments and prioritize efforts to focus on the science themes that SOFIA can do well and can do uniquely => wavelength gap between JWST & ALMA
JWST will offer unprecedented resolution and sensitivity from long-wavelength (orange-red) visible light to the mid-infrared (0.6 to 28 μm).

ALMA offers ~0.01 arcsecond resolution in its highest frequency bands. Band 10 (planned) will extend to 950 GHz (≈ 320 μm).

SOFIA is the only telescope that currently operates in the 28-320 μm wavelength range.

There is great science potential for observing in ALMA-JWST gap.
Major Far Infrared Science Objectives

- Formation of first stars and galaxies in the early universe
  - How and when did the first stars form? => “First Light”
  - What is the subsequent star formation and metal enhancement history?
  - When and how did re-ionization of the universe occur?
  - What were the seeds of Supermassive Black Holes and how did they grow?

- The physics of the interstellar medium and its life cycle
  - How do stars form out of the interstellar medium?
  - Circulation / enrichment / chemical processes of the interstellar medium
  - Supernova explosions & Nova: enrichment, dust formation,
  - Detailed studies of nearby (resolvable) protostars, star forming regions, “mini-starbursts”, Galactic Center, starbursts => templates

- Formation of new solar systems in protostellar disks
  - How do the disks and their outflows form and evolve?
  - How are planetisimals built up out of interstellar dust?
  - How do terrestrial and Jupiter-type planets form and interact with the disk?
  - What is the chemical state (pre-biotic?) of material that enters into planetary atmospheres?

- Cometary, planetary, and satellite bodies and atmospheres
  - Characterizing and understanding all constituents of the solar system
  - History of our Solar System
  - Finding and analysing pristine material in comets
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Emission from Star Forming Regions

Emission from a star forming region (~70K) with spectral lines imposed on the dust continuum.

C+ at 158 µm, the strongest cooling line in the ISM. BICE Galactic maps of C+ at very low spectral resolution (top) and dust emission (bottom).

Dusty galaxies emit mostly in the Far IR. These wavelengths probe their star formation properties and evolution.

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How can the Far IR enhance our Understanding of these Basic Science Themes? (1/2)

General Comments

• Dust continuum emission peaks in the Far IR/submm at cosmological redshifts $0 < z < 5$

• Many important diagnostic molecular & fine structure lines not available from ground (HD, H$_2$O/HDO, OH, other hydrids, fs-lines, bending modes of hot complex molecules, high-J CO)

• Far IR/submm atmospheric “windows” do not permit access to all needed diagnostic lines at any given redshift $z$

• $8 – 12\mu$m PAH features shift into Far IR window beyond $z > 2.5$

Stars, Disks, and Planets

• Structure and characterization of circumstellar disks before, during and after planet-forming stages

• Detection and mapping of large (pre-biotic?) molecules

• Other science: jets and outflows including dust-producing evolved stars, structure and kinematics of molecular clouds and Galactic Center region
Star Formation Activity within nearby Galaxies (1 kpc spatial resolution or better)

- Properties of the interstellar medium (ISM) as a function of location (temperature, density, metallicity, UV radiation hardness and density).
- Star formation rate (SFR) from characteristic Far IR radiation as a function of location (spiral arms, nuclear starburst, etc...) and of local ISM conditions.
- Influence of neighboring galaxies on SFR and ISM properties.

Star Formation History

- Population III stars form via H$_2$ cooling (lowest rotational transitions) of metal-less clouds at cosmological redshifts 10<z<20.
- PAH features and fs diagnostic lines can be used out to reionization epoch to
  - Disentangle radiation due to accretion onto supermassive black holes versus extreme star formation activity.
  - Study metallicity history of the universe.
How can the Far IR enhance our Understanding of these Basic Science Themes? (2/2)

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Spectroscopic sensitivities plotted as spectral survey time in the IR and submillimeter.

The Far IR Surveyor concept has a $4 \times 6$ m off-axis telescope, equipped with R=500 grating spectrometers with 100 beams (at each wavelength) and 1:1.5 instantaneous bandwidth. Detectors are assumed to operate with NEP $= 2 \times 10^{-20}$ WHz$^{-1/2}$. The SPICA / SAFARI-G curve refers to the new SPICA configuration: a 2.5m telescope with a suite of R=300 grating spectrometer modules with 4 spatial beams, and detectors with NEP=$2 \times 10^{-19}$ WHz$^{-1/2}$.

Advances in instrumentation on a 2.5m facility could improve SPICA substantially - the 2.5m probe assumes R=500 grating spectrometers with 15 beams per band, and detector NEP of $4 \times 10^{-20}$ WHz$^{-1/2}$, a sensitivity demonstrated in the lab.

Where is SOFIA's “Sweet Spot”? 

- To obtain highest possible sensitivity, you must cool optics and all detector-visible support structures to 4K
- With SOFIA’s warm optics (2.5m; 30-300μm; 220K)
  - 220K black body peaks at ~15μm
  - Normalized to optical/near-IR wavelengths scales by factor 75 (1.3 inch; 400nm-4μm; 17,000K)
  - Optics, support structure, atmosphere contribute to background
    - Chop between target & empty sky
    - Subtract two large numbers for signal
    - Number statistics limit theoretical sensitivity
Where is SOFIA’s “Sweet Spot”?

• Alternatively, reduce background radiation $F_v \Delta v$ by reducing bandwidth $\Delta v \Rightarrow$ high resolution spectroscopy
  – e.g. GREAT (heterodyne), EXES, HIRMES
  – Detailed studies of emission and absorption lines

• SIAG (Science Instrument Advisory Group) report ranking SOFIA instruments (except GREAT, HAWC+)

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<thead>
<tr>
<th>Rank</th>
<th>Name</th>
<th>Science Instrument</th>
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<tbody>
<tr>
<td>1</td>
<td>FIFI-LS</td>
<td>Field-Imaging Far-Infrared Line Spectrometer</td>
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<tr>
<td>2</td>
<td>FORCAST</td>
<td>Faint Object InfraRed Camera for the SOFIA Telescope</td>
</tr>
<tr>
<td>2</td>
<td>EXES</td>
<td>Echelon-cross-Echelle Spectrograph</td>
</tr>
<tr>
<td>4</td>
<td>FLITECAM</td>
<td>First-Light Infrared Test Experiment Camera</td>
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<tr>
<td>5</td>
<td>HIPO</td>
<td>High-Speed Imaging Photometer for Occultations</td>
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Future of Far IR Science?

• For the science community, SOFIA currently provides the only access to the Far IR in the near future

• SOFIA successor could be lighter-than-air autonomous steerable vehicle (sensitivity is still an issue)

• For a future space-based cryogenic Far IR observatory in the far future, I note
  – Far-IR is not militarily or commercially useful
  – Must conceive, develop, build & test detectors and read-out electronics: very little is “off the shelf”
  – Must have a facility that uses detectors in order to develop them
  – Must have a cadre of interested Far IR scientists and engineers
http://www.sofia.usra.edu