High-Resolution Direct-Detection Spectroscopy with SOFIA

Gordon J. Stacey
Cornell University
Overview

- Address the science applications of HIRMES (now cancelled) and why these capabilities should not be lost
  - Primary application is the investigation of protoplanetary disks
  - Other applications: YSO’s, debris disks, comets, gas giant planet atmospheres, fine-structure line imaging of galaxies, O/H, N/O abundances

- Why use direct detection spectrometers?

- HIRMES description

HL Tau  YSO  Comets  Gas Giants  Galaxies
Protoplanetary Disks

- Over ~ 10 million years, protoplanetary disks evolve into planetary systems
- Bulk of mass is H₂ gas (including H₂, O, H₂O), and ices – all critical to theories of planet formation, but challenging to observe.
Far-infrared spectroscopy is critical to our understanding of planet formation – and SOFIA holds the keys
Far-infrared Lines Important

The critical building blocks for the formation of planets include water, oxygen, and molecular hydrogen

- Water is a key ingredient for life:
  - Emits strongly in its far-infrared rotational lines, but is nearly impossible to observe from the ground – because of the telluric lines, hence airborne astronomy…

- Oxygen is key ingredient for life:
  - Product of the photodissociation of $\text{H}_2\text{O}$, $\text{CO}_2$, and CO ices that are released during collisions between planetesimals.
  - Critical to understanding the formation of the gas and ice giants, and terrestrial planet atmospheres.

- Hydrogen is primary component of protostellar disks, since it carries most of the mass
  - But its role is poorly understood since it is so difficult to observe.
Water and Ice

- Water is central to our understanding of the formation of habitable worlds
- Beyond the “snow line” is it mostly ice
- Within the habitable zone water is gaseous
  - Terrestrial planets likely form “dry” since this water is photodissociated before incorporation
  - Water transported in from beyond snow line in later phases by icy bodies
Detect ice through its strongest features near 40 μm in emission

- Shorter wavelength bands in absorption, since warm (emitting) ice would melt

Emission arises from small icy grains above the colder disk

Feature strength & shape yields mass, and ice/rock ratios critical for core-accretion formation models

Ice features not available to other facilities so this is not well explored observationally
Protoplanetary disks are mostly gaseous: Gas:Dust is 100:1 by mass

Mostly, H$_2$ – a very weak emitter since first (quadrupole) emitting level is 550 K above ground, and the disk temperature is only a few 10’s of K

CO proxy is not very good, since “conversion factor” varies by orders of magnitude ⇒ masses of PPD totally unconstrained

HD is a good proxy: low-lying 128 K, 385 K, ....) rotational lines
- J = 1-0 112 μm
- J = 2-1 56 μm

HIRMES could detect the HD 1–0 line at 112 μm in disks of masses >10$^3$ M$_{\odot}$ around stars of > 1 M$_{\odot}$. The figure shows model predictions for HD 1–0 line fluxes (circles), along with detections (stars) and upper limits from Herschel-PACS. All models and data are scaled to a distance of 125 pc.
Neutral Oxygen: Disk energetics

- [OI] 63.2 μm is typically the most luminous emission line of protoplanetary disks
  - Most commonly detected line from disks by Herschel-PACS
    - Interpretation limited by lack of ability to distinguish ~10 km/s disk emission from 100 km/s outflows and shocks.

- HIRMES will produce velocity-resolved [OI] spectra of more than 30 protoplanetary disks
  - These data will determine the origins of emission disk/outflows
  - Radial surface energy and mass from 1-100 AU.

Simulated HIRMES spectra of TW Hya (a disk with typical line strengths). The signal-to-noise on [OI] 63.3 μm (left) and HD 1-0 (right) correspond to 1.5 and 10 hours of observing time with overheads.
- Velocity resolve spectral lines
- Place radial distance in the emitting disk assuming Keplerian orbits.
- O and H$_2$O are likely in and around the snow line while HD is external $\Rightarrow$ HD requires less velocity resolution than O and H$_2$O observations
Uniqueness

- Water, [OI], HD and H₂ detected by Hershel/Spitzer, but not with the resolving power necessary for tomography, and/or at the necessary sensitivity.
- JWST will detect some of these lines, but not at the required resolving power.
- ALMA has so far detected just one water line from PPD - many available to HIRMES to outline excitation as a function of distance from the central star.
Why not heterodyne spectroscopy?
Direct vs. Coherent Detection

- Direct detection refers to detectors that detect the energy of the photon
  - Photo-electrons in semi-conductor, or warming the crystal lattice in a silicon bolometer
  - For high resolving powers \((10^5)\) at 112 \(\mu\)m, interference paths 5.6 m long are necessary (in free space)! – but a FPI folds the path….

- Coherent detection refers to detectors that detect the wave nature of the light
  - Typically coherent detectors measure the source signal that is in phase with a strong monochromatic local oscillator
  - Very high resolution spectroscopy can be performed at low radio frequencies, digitally.
Why Direct Detection?

- Direct detection is inherently more sensitive than coherent detection
  - Detection of phase leads to “quantum noise”: $T_{QN} = \frac{h \nu}{k}$
    - $580 < T_{QN} < 130 \text{ K as } 25 \text{ \mu m} < \lambda < 112 \text{ \mu m}$
  - Typical noise temperatures are: $5 \cdot T_{QN} \text{(DSB)} \Rightarrow 5800 \text{ to } 1300 \text{ K}$

- Direct detection devices do not detect phase. In the best case they are “background limited”
  - One can show that for reasonably efficient systems ($\tau_{cold} 20\%$):
    - $T_{BLIP,RJ,SSB} = \frac{T_{warm}}{\sqrt{\tau_{cold}}} \approx 150 \text{ to } 330 \text{ K (25 – 122 \text{ m})}$
    - $T_{BLIP,RJ,SSB} = 160 \text{ K (SSB) @ 112 \text{ \mu m HD (J = 1 – 0)}}$
HIRMES

- High resolution (RP ~ 10^5) far-IR spectrometer based on direct detection
- Selected as the 3rd generation SOFIA instrument
- Close to integration and test – cancelled on April 1, 2020 due to cost and schedule overruns – driven by challenges with detectors
- Revival in the cards when these challenges are overcome

PI: Matt Greenhouse (GSFC); FPI developed at Cornell; Science Team Lead (Gary Melnick)

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Institution</th>
<th>Investigator</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arendt, Richard*</td>
<td>UMBC</td>
<td>Pontoppidan, Klaus</td>
<td>STScI</td>
</tr>
<tr>
<td>Bergin, Edwin</td>
<td>U. Michigan</td>
<td>Richards, Samuel*</td>
<td>USRA</td>
</tr>
<tr>
<td>Bjoraker, Gordon</td>
<td>GSFC</td>
<td>Roberge, Aki</td>
<td>GSFC</td>
</tr>
<tr>
<td>Chen, Christine*</td>
<td>STScI</td>
<td>Rostem, Karwan*</td>
<td>UMBC</td>
</tr>
<tr>
<td>Kutyrev, Alexander</td>
<td>U. Maryland</td>
<td>Stacey, Gordon</td>
<td>Cornell U.</td>
</tr>
<tr>
<td>Melnick, Gary</td>
<td>Harvard U.</td>
<td>Tolls, Volker*</td>
<td>Harvard U.</td>
</tr>
<tr>
<td>Milam, Stefanie</td>
<td>GSFC</td>
<td>Su, Kate*</td>
<td>U. Arizona</td>
</tr>
<tr>
<td>Moseley, Harvey</td>
<td>GSFC Emeritus</td>
<td>Watson, Dan</td>
<td>U. Rochester</td>
</tr>
<tr>
<td>Neufeld, David</td>
<td>Johns Hopkins U.</td>
<td>Wollack, Edward</td>
<td>GSFC</td>
</tr>
<tr>
<td>Nikola, Thomas*</td>
<td>Cornell U.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Investigator added via Legacy Science Investigation proposal
HIRMES Fact Sheet

- A direct detection spectrometer covering the spectral range from 25 to 122 μm

- Four spectroscopic modes to HIRMES
  - High-res mode: RP ~ 50,000 → 100,000
  - Mid-res mode: RP ~ 10,000
  - Low-res mode: RP ~ 600
  - Imaging spectroscopy mode: RP ~ 2000

- Modes optimized for the science goals.

- HIRMES uses:
  - Background limited bolometers
  - Combination of Fabry-Perot Interferometers and gratings
Achieving High RP w/ Fabry-Perots

<table>
<thead>
<tr>
<th>Mode</th>
<th>Scanning FPI</th>
<th>Central Wavelength</th>
<th>Wavelength Range</th>
<th>Resolving Power</th>
<th>Etalon Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>slit</td>
<td>high-R LW</td>
<td>112 μm</td>
<td>86-122 μm</td>
<td>100,000</td>
<td>100 mm</td>
</tr>
<tr>
<td>slit</td>
<td>high-R MW</td>
<td>63 μm</td>
<td>50-86 μm</td>
<td>100,000</td>
<td>90 mm</td>
</tr>
<tr>
<td>slit</td>
<td>high-R SW</td>
<td>35 μm</td>
<td>25-36 μm</td>
<td>50,000</td>
<td>90 mm</td>
</tr>
<tr>
<td>slit</td>
<td>mid-R LW</td>
<td>112 μm</td>
<td>86-122 μm</td>
<td>12,000</td>
<td>90 mm</td>
</tr>
<tr>
<td>slit</td>
<td>mid-R MW</td>
<td>63 μm</td>
<td>50-86 μm</td>
<td>12,000</td>
<td>90 mm</td>
</tr>
<tr>
<td>slit</td>
<td>mid-R SW</td>
<td>35 μm</td>
<td>25-36 μm</td>
<td>12,000</td>
<td>90 mm</td>
</tr>
<tr>
<td>imaging</td>
<td>low-R SW</td>
<td>57 μm</td>
<td>50-70 μm</td>
<td>2000</td>
<td>30 mm</td>
</tr>
<tr>
<td>imaging</td>
<td>Low-R LW</td>
<td>102 μm</td>
<td>80-125 μm</td>
<td>2000</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

HIRMES high (top) and low (bottom) resolution scanning etalons

HIRMES fixed etalon imaging filters

Grating delivers RP = 600

HIRMES diffraction gratings
Detector Arrays

- Membrane absorber, TES bolometers for optimal sensitivity
- Subarrays: imaging and long slits
- Challenges
  - Point source sensitivity optimization requires \( \frac{\lambda}{D} \approx f \# \times \lambda \) pixels \( \Rightarrow \) need series of arrays 3.4 to 1 in scale
  - Maximizing DQE requires a back-shot
  - NEP’s challenging, but not exceptionally so, and have been demonstrated – challenges are architecture and readout
  - Longest wavelength, largest pixels, and the most demanding NEP requirements \( \Rightarrow \) demands on architecture

<table>
<thead>
<tr>
<th></th>
<th>Dark Detector NEP ( 10^{-18} ) W Hz(^{-1/2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Resolution</td>
<td>20</td>
</tr>
<tr>
<td>High Resolution</td>
<td>3</td>
</tr>
</tbody>
</table>

16 x 64 pixel format: 6.1 arcsec/pixel

8 Pixels, 2.5-8.5 arcsec/pixel

A tilted mirror is used to create an integrating cavity that is tuned to \( 3 \lambda/4 \) at the center of each pixel

128 Pixels, 2.5-8.5 arcsec/pixel

\[ \text{NEP's} \text{ challenging, but not exceptionally so, and have been demonstrated – challenges are architecture and readout} \]
Steps toward Integration and Test
Cryogenic optics alignment verification

Warm test set-up. Cryogenic test is performed using a fused silica cryostat pressure window.

Cryogenic OGSE (tooling balls and fiber sources) is located in place of the FPA to support the double pass test.
Double-pass alignment test

The grating mechanism carries 3 diffraction gratings and 1 mirror. It provides +/- 180 degree rotation with 8 arc-sec precision and stability.

The pupil adjust mechanism enables alignment of the HIRMES entrance pupil with the telescope secondary mirror. It provides +/- 3 degrees tile in two axis with 1 arc-min precision and stability.
Key elements of the HIRMES mK cooling system

ADR Cooler

He$^3$/He$^4$ Sorption Cooler

Optical Bench Back Side: CD-0B Assembly Level

ADR Heat Switch

Heat Switch Thermal Interface
Each unique observation requires setting 6 mechanisms

<table>
<thead>
<tr>
<th>Spectroscopy Mode</th>
<th>X Denotes Element in Beam Line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HR Scanning FPI</td>
</tr>
<tr>
<td>High Resolution</td>
<td>X</td>
</tr>
<tr>
<td>Medium Resolution</td>
<td>X</td>
</tr>
<tr>
<td>Low Resolution</td>
<td></td>
</tr>
<tr>
<td>Imaging</td>
<td></td>
</tr>
</tbody>
</table>

Medium-R FPI selection wheel
High-R FPI selection wheel in test
Slit selection wheel
Filter selection wheel
Spatial scanning

- Gets above 1/f noise and removes sky background, minimizes losses
- FPI transmits to blue off-axis
  - Lissajous or Box scan patterns for spectroscopy imaging
  - Scans along slit for high-res modes

Simulated line profile of a rotating disk showing 11 scans at nominal wavelengths to sample the line profile. Additional sampling appears as the source is scanned up and down the slit by ±2 pixels.

SOFIA workshop June 22-24: Building the 2020-2025 Instrument Roadmap
Imaging Spectroscopy Mode example:

- **M83**: [OIII] × 2, [NIII], [NII]
  - Ionization/stellar populations
  - Obscured star formation
  - Metallicity O/H, N/O → SF history
- **[OIII]**: 52 μm
  - Line flux: 6 × 10^{-17} W/m^2
  - 12 σ in 15 minutes
  - 30 pointings → 7.5 hours
- All lines: additional 1 × 7.5, 2 × 3.0 hrs
  - **Total**: 21 hours for complete [OIII] × 2, [NIII], [NII]
Summary

- High resolution direct detection spectroscopy is a *unique and compelling* niche for SOFIA
  - Tomographic locations of the building blocks of planetary systems
  - YSO’s, debris disks, comets, gas giant planet atmospheres
- The HIRMES spectrometer was funded and built to pursue this science and enabled much more such as:
  - Velocity resolved spectroscopy of galaxies
  - Efficient imaging of galaxies in fine-structure lines
- HIRMES encountered challenges with detector arrays
- Revival of HIRMES in the cards when these challenges are overcome
Thanks!