Molecular spectroscopy in the FIR – what is SOFIA doing?

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Outline

• Short overview of SOFIA
• The first generation instruments, highlighting only two: GREAT and EXES
• FIR infrared spectroscopy (and some MIR)
• A few highlights from GREAT obtained during Short and Basic Science
• Future
SOFIA Overview

- **2.5-m telescope in a modified Boeing 747SP aircraft**
  - Imaging and spectroscopy from 0.3 µm to 1.6 mm, especially the obscured IR (30-300 µm)

- **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
  - Short and Basic Science in 2011: 17 flights for the community with FORCAST and GREAT; 35 science flights in total
  - 20 year design lifetime – can respond to changing technology
  - Science Ops at NASA-Ames; Flight Ops at Dryden FRC (Palmdale- Site 9)
  - Deployments to the Southern Hemisphere and elsewhere
  - Goal is >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
The SOFIA Observatory

Telescope and Optical Layout

SOFIA Test flight on July 13, 2010
Photometric Sensitivity and Angular resolution

SOFIA is as sensitive as ISO

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 First Generation Instruments

The Seven First Generation SOFIA Science Instruments (SIs)

Cycle 1
Spectroscopic Capabilities

- GREAT
- EXES
- FIFI LS
- HIPO
- FLITECAM w/ grisms
- FORCAST w/ grisms
- FORCAST
- HAWC
**GREAT: Heterodyne Spectrometer**
German REceiver for Astronomy at Terahertz frequencies

- **PI:** R. Güsten, Max-Planck Institut, Bonn ([guesten@mpifr-bonn.mpg.de](mailto:guesten@mpifr-bonn.mpg.de))
- **Detector:** dual channel hot-electron bolometer (HEB): Low: 1.252 – 1.352; 1.417 - 1.520 THz (240 - 200 µm) & 1.815 - 1.91 THz (165 - 155 µm) Mid: 2.507 – 2.514; 2.67 – 2.68 THz (120 - 110 µm)
- **L-channel fill in most of the Herschel HIFI gap between band 5 & 6**
- **Backends:** AOS & XFTTs (2.5GHz BW, 44 kHz res (64k channels)) \(R=10^6 \rightarrow 10^8\)
- **Science:** Spectroscopy of CII (158 µm), HD (112 µm), and many other molecules
- **Targets:** Galactic and extragalactic ISM, circumstellar shells
- **Single-sideband (SSB) noise temperature:** \(T_{\text{SYS}} \sim 4000 \text{ K at 158 µm}\)
- **High frequency 4.7 THz channel targeting** [O I] 63 µm expected in 2013
- **Also small 7 beam L2 array (up-GREAT)**
GREAT on the SOFIA Telescope
# Echelon-Cross-Echelle Spectrograph 
**EXES**

- **Pl**: Matthew J. Richter, UC Davis
- **Echelon Spectrograph, 4.5 – 28.3 μm**  
  \( R=10^5, 15000, \text{ or } 4000 \)
- **Detector**: \( 1024^2 \) IBC detector
- **Slit width range**: 1” – 4”
- **Mode**:  
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<tr>
<td>Low</td>
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FIR spectrum of Sgr B2 taken with the ISO/LWS. Taken from Goicoechea & Cernicharo (2009, Spica Workshop) and based on work by Goicoechea et al. (2004) and Polehampton et al. (2007)
FIR Infrared Spectroscopy

• The Sgr B2 spectrum shows that in the FIR we usually do not see the rich emission line spectra that we see at mm and sub-mm wavelengths. Instead the spectrum is dominated by:
  – Fine structure lines of [OI], [OIII], [CII], [NII], and [NIII], which are often the most important cooling lines of the ISM
  – Light molecules like OH, OD, HD, H$_2$D$^+$, H$_2$O and many other hydrides
  – Organic chemistry, symmetric molecules lacking permanent dipole moment, but which show vibration-rotation transitions in the FIR and Mid IR: C$_2$H$_2$, CH$_4$, CO$_2$, C$_6$H$_6$, and pure carbon chains C$_n$
• Most hot cores optically thick in the FIR, which is why we do not see high-J lines tracing hot, dense gas
• We may still see them in PDRs, SNe remnants and in circumstellar shells around evolved stars
• Hot cores provide strong background sources for absorption studies, but
  – Lines are narrow, hence we need heterodyne receivers (see e.g. OD, SH, HD etc)
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 Λ doublet at 18 cm wavelengths is well studied (both thermal and maser), but this emission is dominated by relatively cool, diffuse gas ($n \sim 10^3$ cm$^{-3}$) and the excitation temperatures frequently deviate from LTE.

• The FIR rotational lines of the OH $^2\Pi_{1/2}$ and $^2\Pi_{3/2}$ are observable with GREAT and probe denser, hotter gas than the 18 cm lines.

• Chemistry of OH closely tied to $H_2O$, both in formation of $H_2O$ and its destruction through photo dissociation.
The 119 µm line (2.514 THz) is covered by the GREAT M-channel and ideal for absorption line studies of diffuse gas in front of strong UC HII regions (hot cores). The 163 µm line (1.8378 THz) falls into the GREAT L2-channel and is seen in emission.
Absorption studies of OH

- Critical density of $J=5/3$ to $3/2 \sim 5 \times 10^9$ cm$^{-3}$
- All the OH in absorbing clouds in the ground state
- Hence accuracy of column density determinations only depend on SNR and on how well we can determine the continuum level
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 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
$\text{OH} \, ^2 \Pi_{1/2}, \, J = 3/2 - 1/2 \, (163 \, \mu\text{m})$

- These observations show that the observed line intensities require a compact region of warm gas with high OH abundance.
Discovery of interstellar mercapto radicals (SH) – Neufeld et al. 2012 (A&A 542, L6)

- SH is one of the simplest hydrides previously undetected in the ISM (in the gap between the HIFI band 5 & 6)
- Its ground state rotation line at 1.383 THz (217 microns) shows Lambda-type doubling (nuclear rotation-electron spin interaction), therefore it is easy to identify
- Seen in absorption towards W49N, both local gas and intersecting spiral arm
The observed abundance of SH compared to SH$^+$ and $\text{H}_2\text{S}$ require a “warm chemistry”, driven by shocks or turbulent dissipation, that can enable endothermic formation paths.
Detection of interstellar OD in absorption against IRAS 16293-2422; Parise et al. 2012 (A&A, 542, L5)

- First detection of OD outside of the solar system.
- The observed OD/HDO abundance of 17-90 is high compared to model predictions
- Dissociative recombination of H$_2$DO$^+$ into OD and H$_2$O may cause HDO depletion
Future for SOFIA

• GREAT will continue studies of Deuterium abundances especially using HD (112 µm; 2.67499 THz)

• In 2014 EXES will be commissioned and we have a fantastic instrument for high resolution spectroscopy in the mid-IR

• Future SOFIA instruments may offer additional opportunities