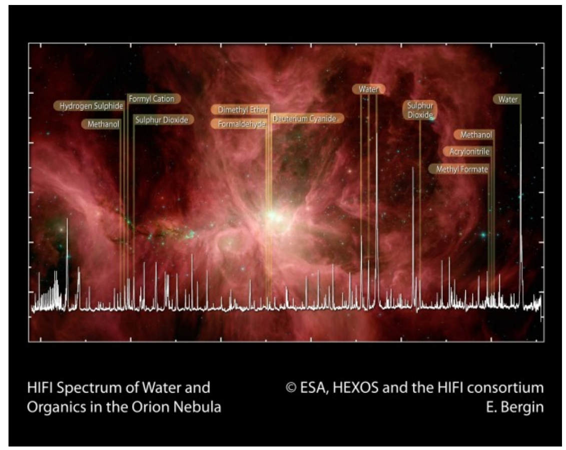
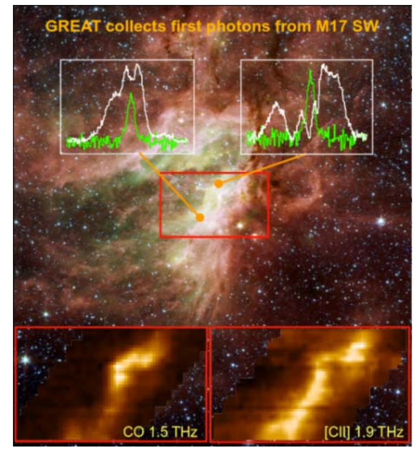
Infrared Spectroscopic Studies with the Stratospheric Observatory for Infrared Astronomy (SOFIA)





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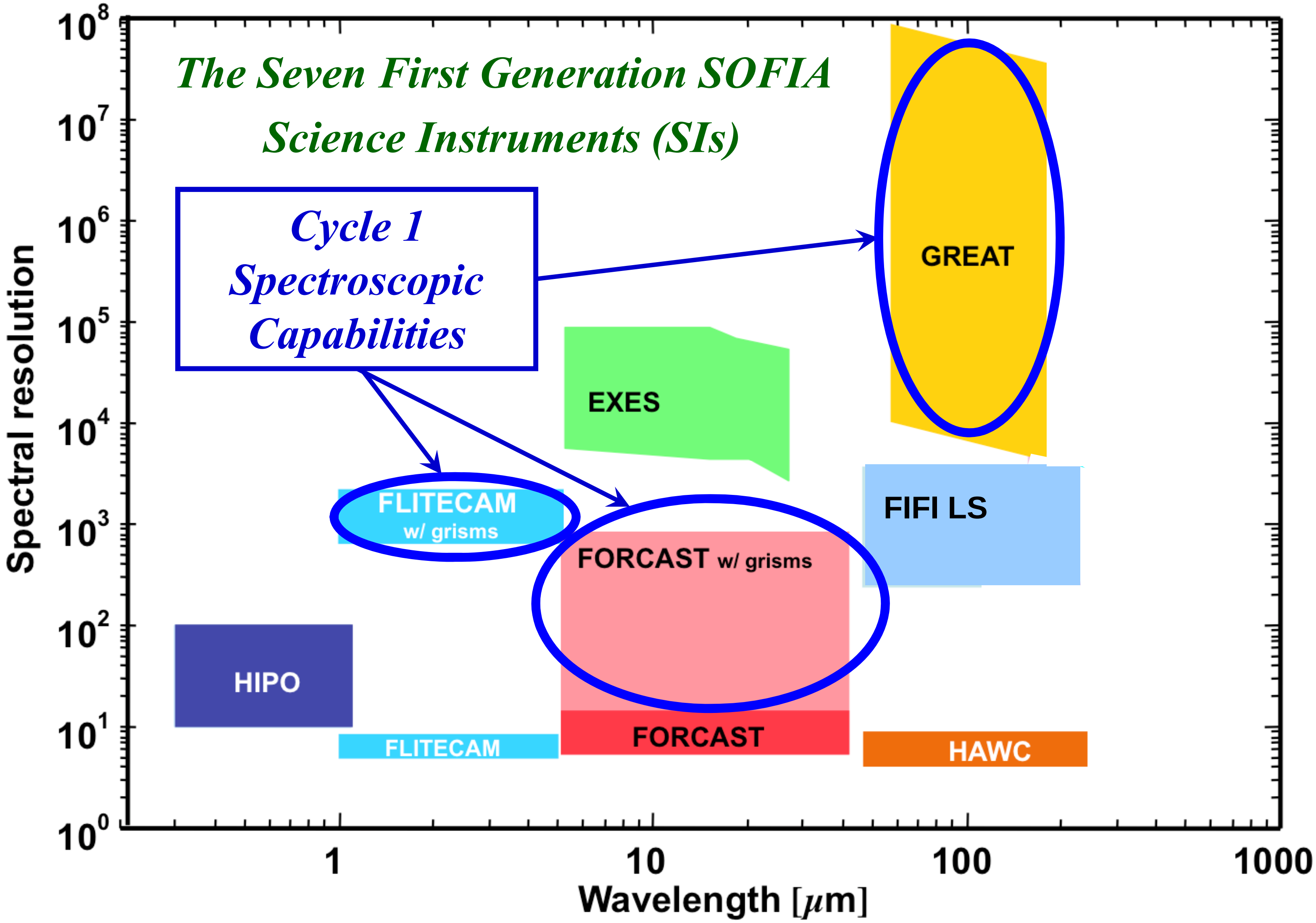
This talk is at: *http://www.sofia.usra.edu/Science/speakers/index.html*

Outline

- *SOFIA Spectroscopy: the Chemical Evolution of the Universe*
- *Early Science with GREAT*
- *Future SOFIA Spectroscopic Science*

SOFIA First Generation Spectroscopy

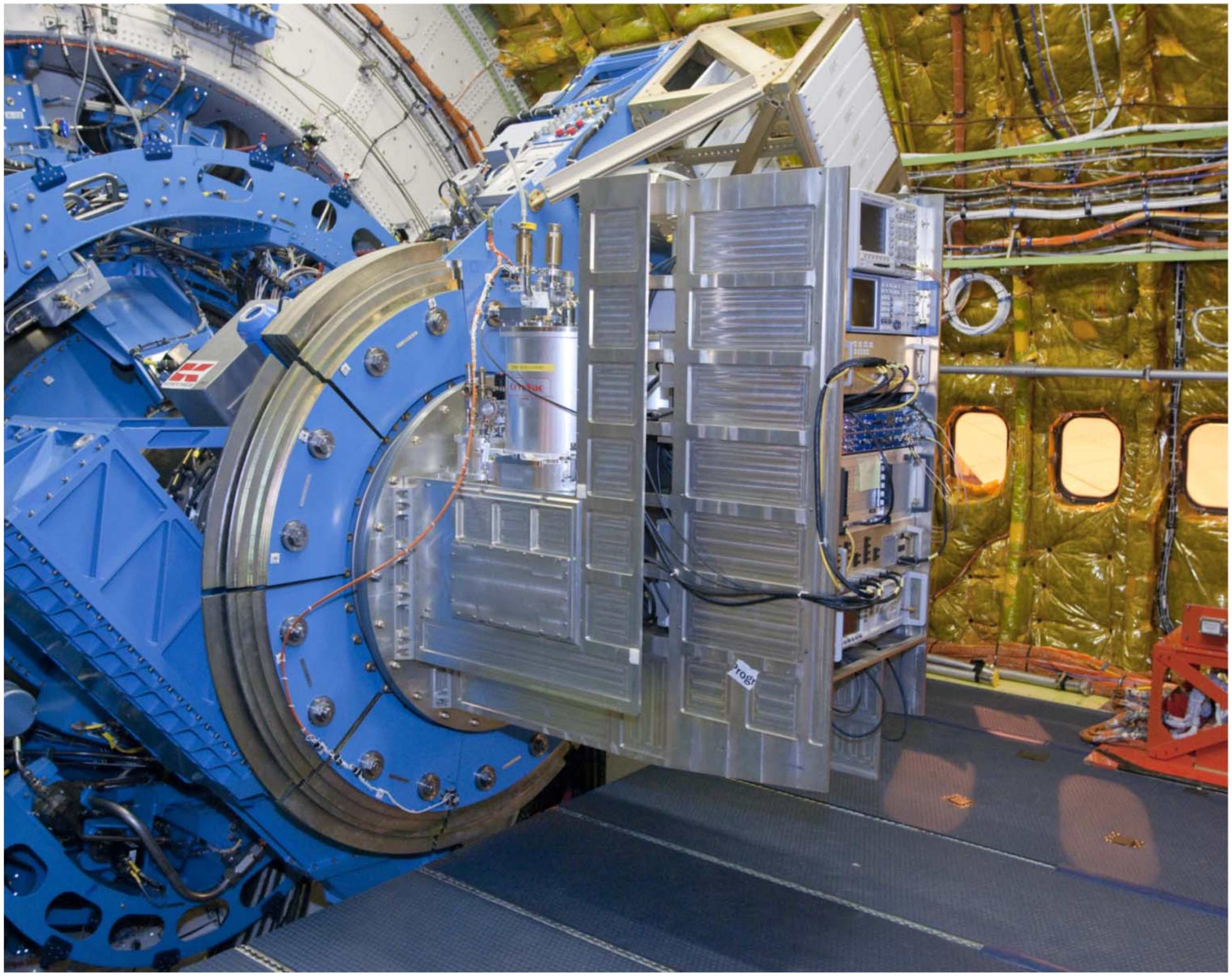


Basic Science Spectroscopy with GREAT

GREAT: Heterodyne Spectrometer

- *PI: R. Güsten, Max-Planck Institut, Bonn (guesten@mpifr-bonn.mpg.de)*
- *Detector: dual channel hot-electron bolometer (HEB): Low: 1.25 - 1.50 THz (240 - 200 µm) & 1.82 - 1.92 THz (165 - 155 µm) Mid: 2.50 - 2.70 THz (120 - 110 µm)*
- *Field of View: single element*
- *$R = 10^6 \rightarrow 10^8$*
- *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: $T_{SYS} \sim$ 4000 K at 158 µm*
- *High frequency 4.7 THz channel targeting [O I] 63 µm expected in 2013*

GREAT on the SOFIA Telescope



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~ 10^3 cm^{-3})***

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

OH level diagram

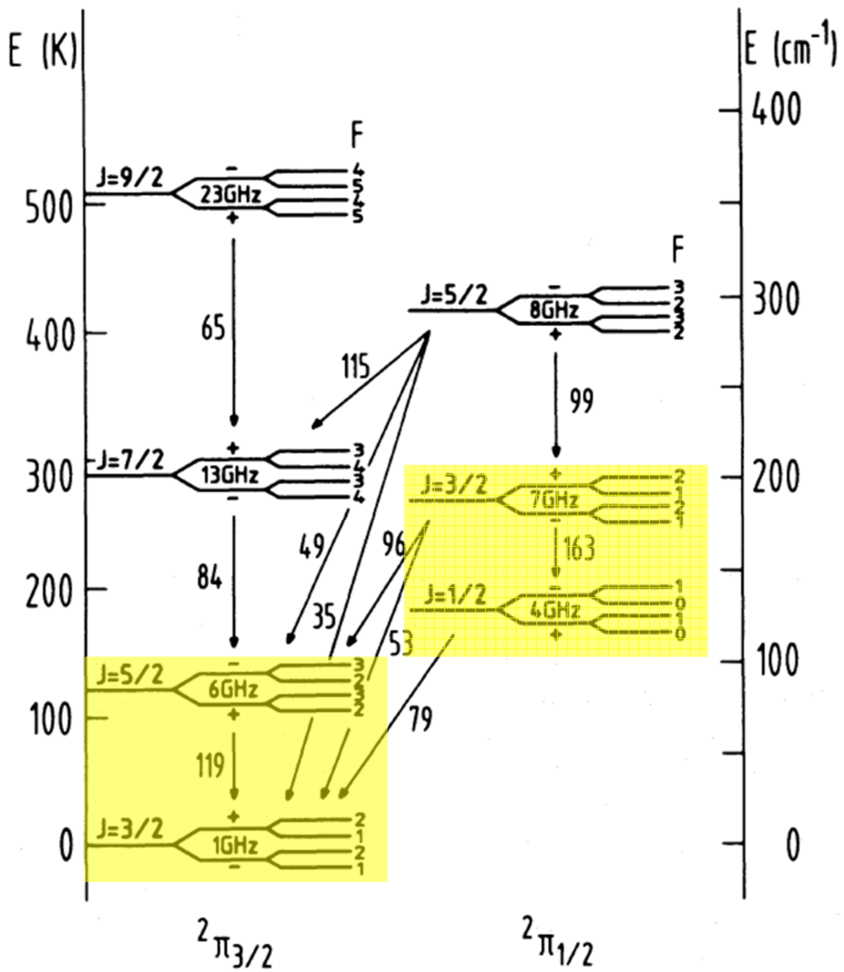
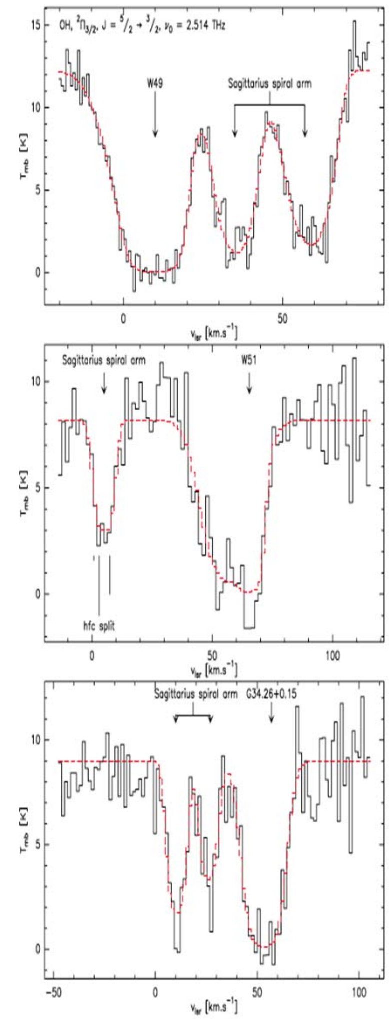


Fig. 1. Schematic representation of the lowest 28 energy levels of ^{16}OH. The Λ doubling and hyperfine splitting are not shown to scale.

- ***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.***

OH $^2\Pi_{3/2}$ J = 5/2 ← 3/2 (119 μm)

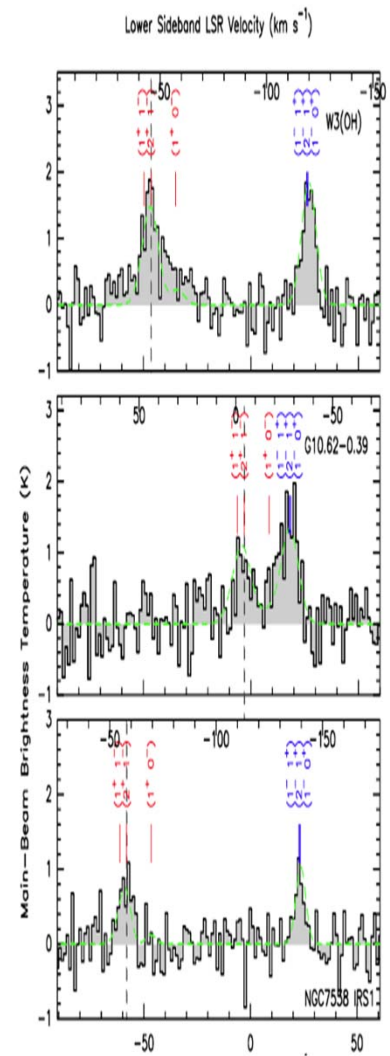
- ***Wiesemeyer et al. (2012, A&A, 542, L7) observed the 119 μm OH ground state line in absorption towards several ultra compact HII regions.***
- ***This is the first velocity resolved spectrum ever observed of this transition***
- ***The line traces molecular gas in the spiral arm clouds along the line of sight and near the HII regions.***
- ***Using Herschel observations of H_2O, they find that the H_2O to OH abundances ranges from 0.3 – 1.0***



OH $^2\Pi_{1/2}$, J = 3/2−1/2 (163 μm)

- ***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)***

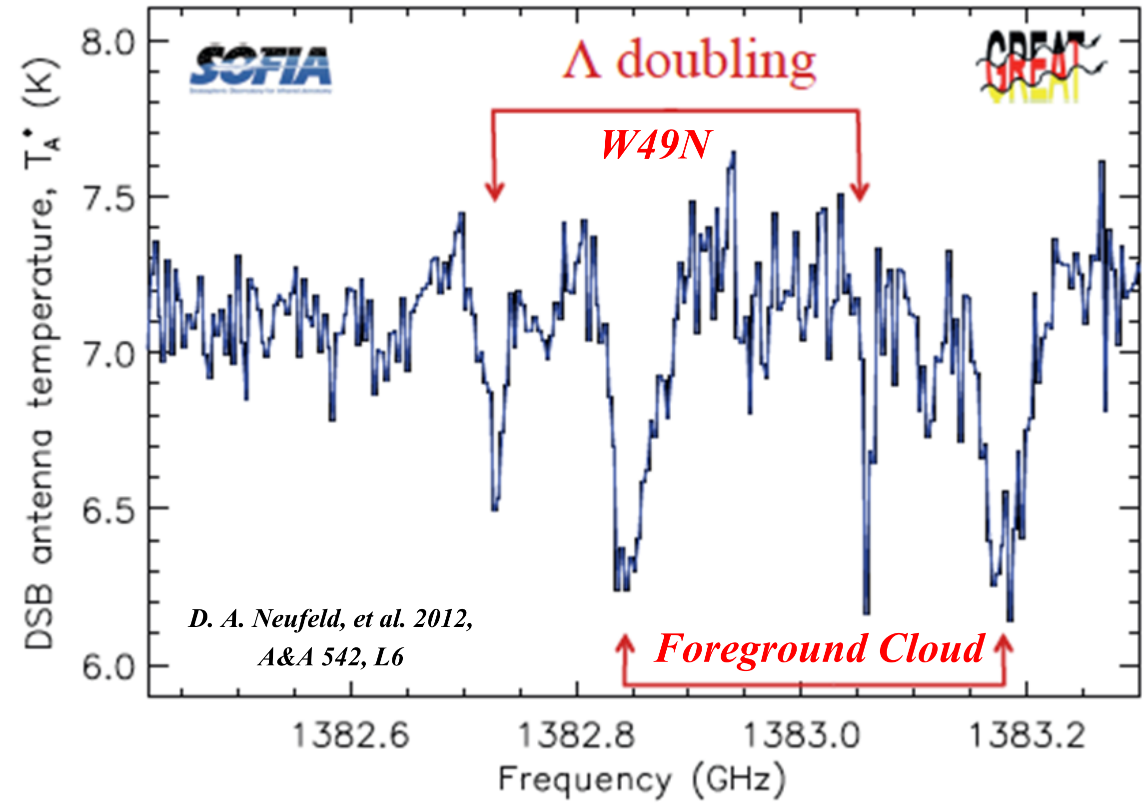
- ***These observations show that the observed line intensities require a compact, high OH column density, warm gas component***



Discovery of SH (Mercapto radicals) in Interstellar Space

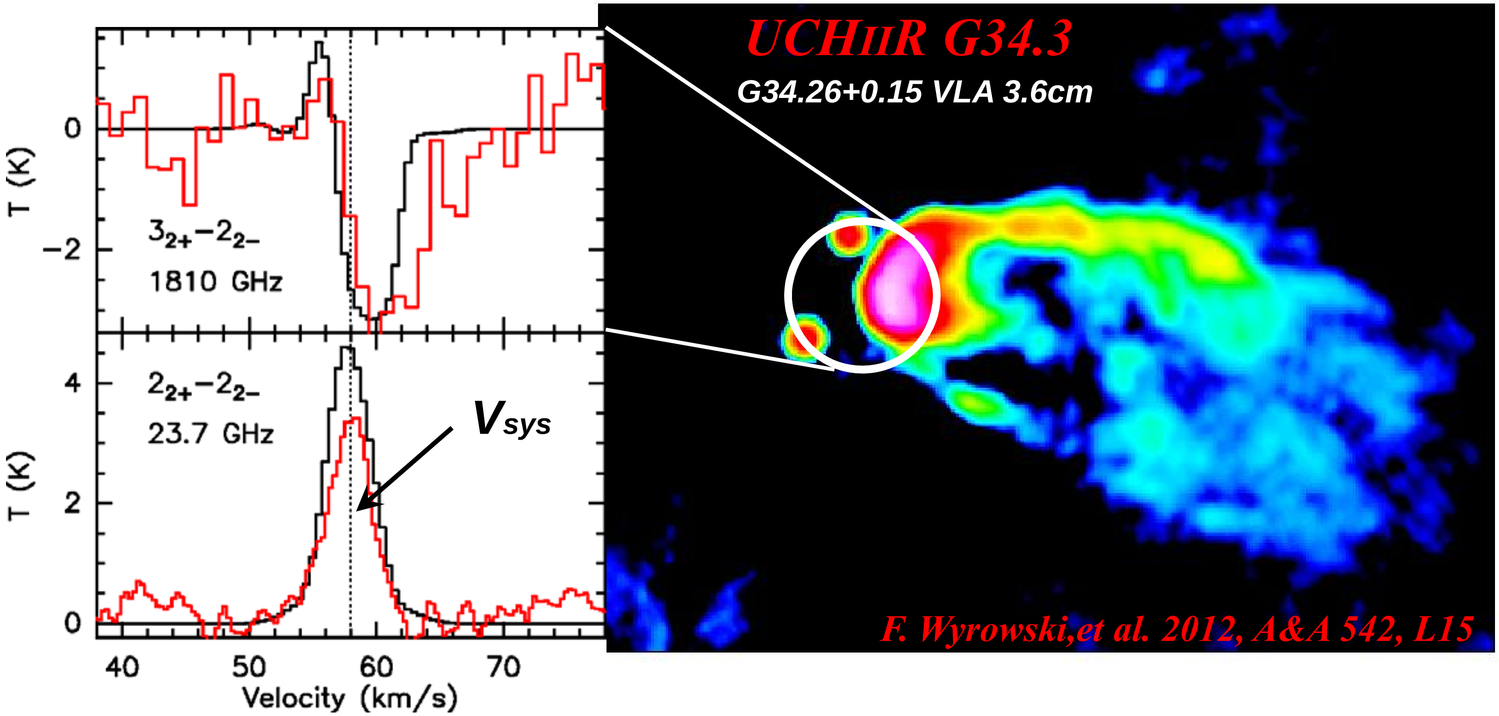
- *SH is one of the simplest Hydrides previously undetected in the ISM*
- *Its ground state rotation line at 1.383 THz (217 microns) shows Lambda-type doubling (nuclear rotation-electron spin interaction), so it is easy to identify*
- *W49N intersects several molecular clouds in it own and another spiral arm that cause absorption of the continuum*.

Mercapto Radicals in Absorption Toward W49N



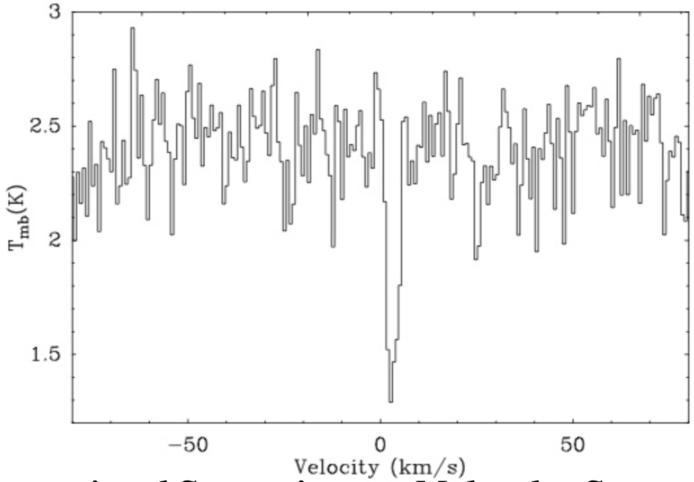
- *Hydrogen Sulfide (H_2S) is seen in absorption at the same velocities*
- *The implied diffuse cloud abundance ratio, $SH/H_2 \sim 10^{-8}$, suggests the presence of elevated gas temperatures (~1000K) within cloud cores*

Probing Protostellar Infall with Terahertz Ammonia Absorption in an Ultra Compact HII Region



- ***Red-shifted ammonia (NH_3) absorption due to infall detected against the optically thick dust continuum***
- ***Optically thin $C^{17}O$at 1.27 cm (23.7 GHz) gives the systemic velocity***

Detection of OD Absorption towards the Low-mass Protostar IRAS 16293-2422



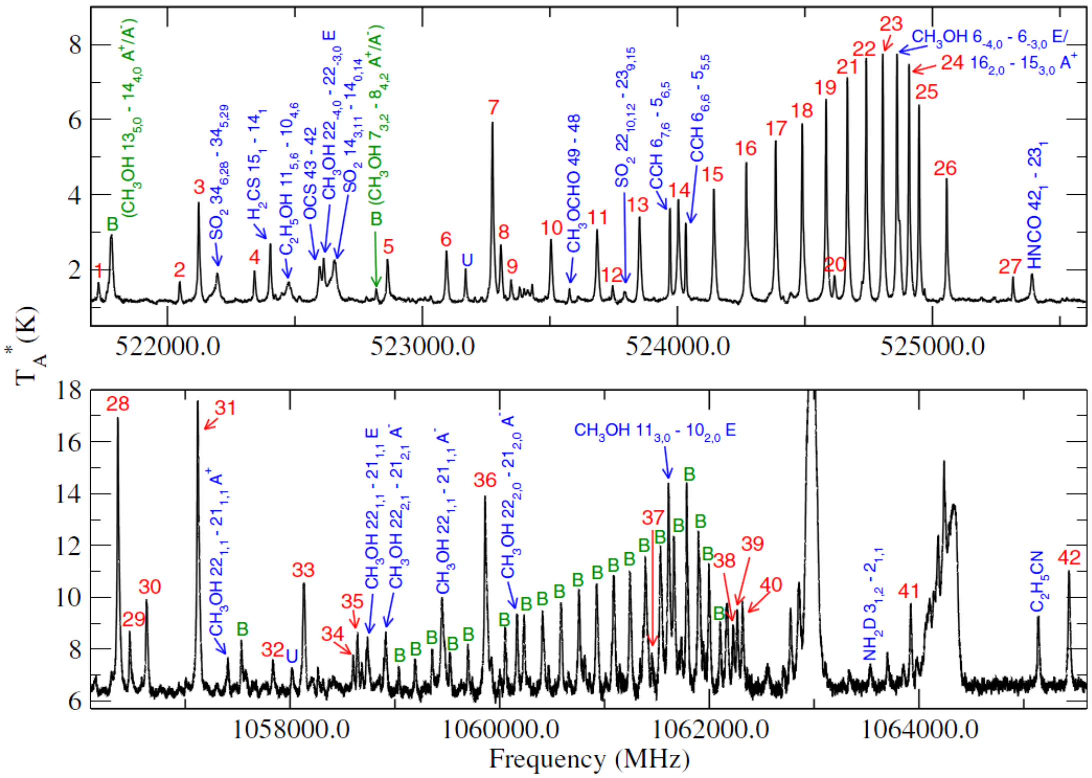
B. Parise - AAS SOFIA Splinter Session 09.01.2012

- *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 H_2DO^+ into OH and H_2O may cause HDO depletion*

Future Molecular Spectroscopy with SOFIA

Name	Spectroscopic Capability	PI	Institution (Year of Commisioning)	Wave-lengths (μm)	Spectral Resolu-tion
FORCAST	Grism Spectrometer	T. Herter	Cornell (2013)	5-40	200
GREAT	Heterodyne Spectrometer	R. Güsten	MPIfR (2011-13)	60-240	10^6-10^8
FLITECAM	Grism Spectrometer	I. McLean	UCLA (2013)	1-5	2000
EXES	Mid-Infrared Spectrometer	M. Richter	UC Davis (2014)	5-28	3000, 10^4, 10^5
FIFI-LS	Integral Field Far-Infrared Spectrometer	A. Krabbe	U Stuttgart (2014)	42-210	1000-3750

Molecular Emission from Star Forming Clouds



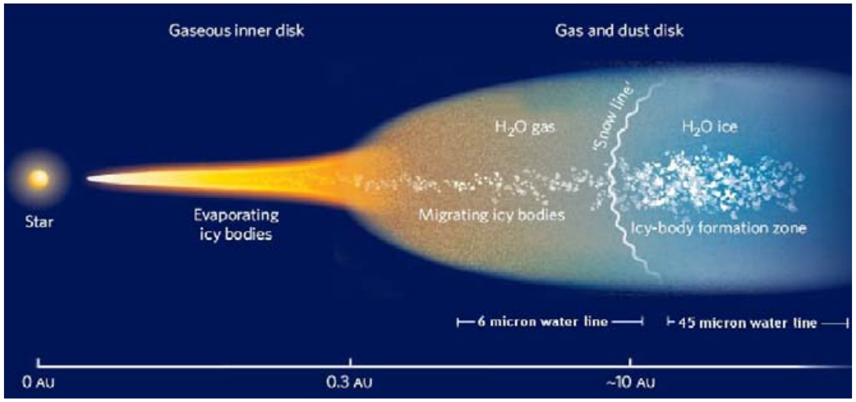
Herschel HIFI spectrum of methanol and other organic molecules toward the Orion KL nebula (S. Wang et al. 2011, A&A, 527, A95)

- *SOFIA is the only mission in the next decade that is sensitive to the entire Far-IR SED of regions of star formation*

- *These are dominated by emission from molecules usually excited by radiation from massive stars and supernova shock waves*

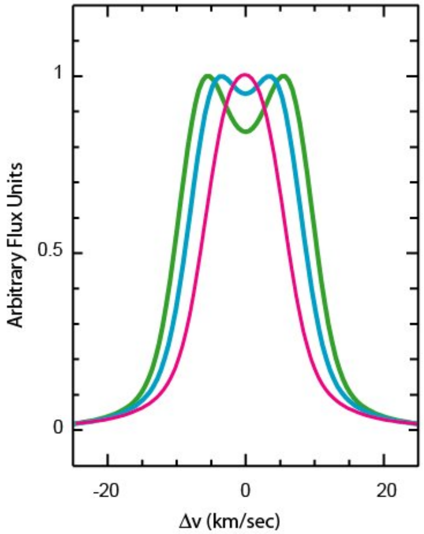
EXES: The chemistry of disks with radius and Age

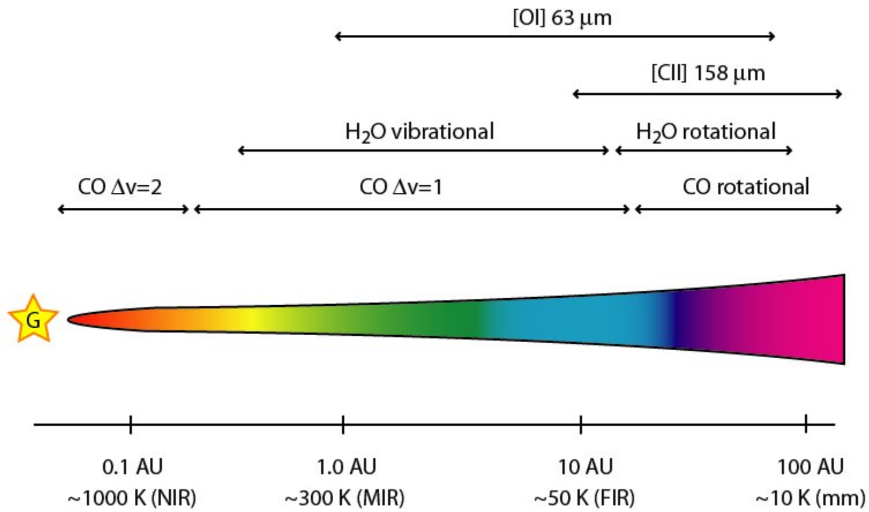
- *High spatial and spectral resolution can determine where different species reside in the disk*



- *small radii produce double-peaked, wider lines.*

- *Observing many disks at different ages will trace disk chemical evolution*

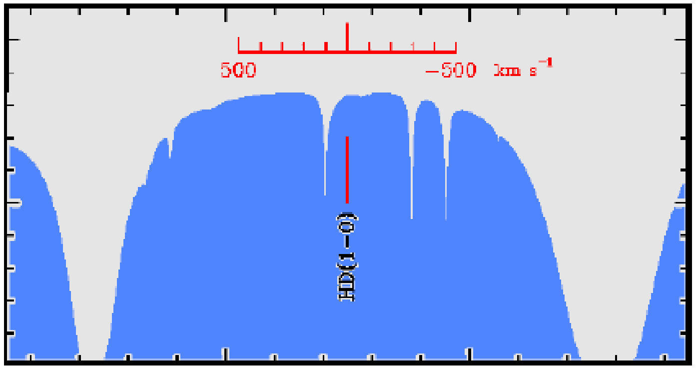




GREAT Observations of ISM HD

- The 112μm ground-state rotational line of HD is accessible to GREAT
- ISO detection of SGR B shows HD column densities of ~ $10^{17} – 10^{18}$ cm^{-2} can be detected by GREAT on SOFIA

- All deuterium in the Universe was originally created in the Big Bang and is destroyed by nucleosynthesis in stars



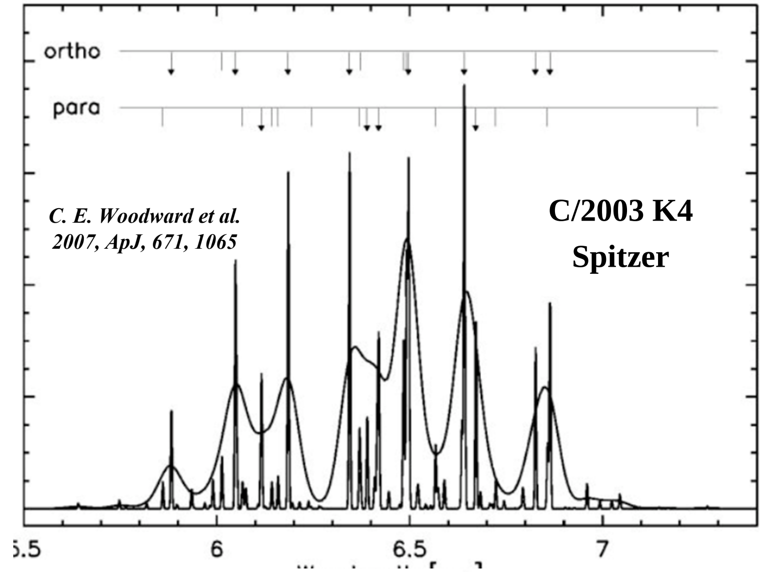
Atmospheric transmission around the HD line at 40,000 feet

- Therefore, D abundance probes the ISM that has never been cycled through stars

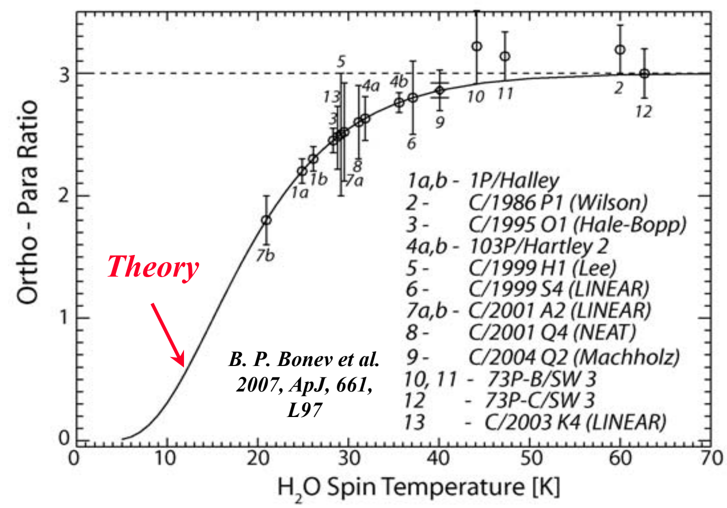
- 112 μm observations of HD can be used to determine ISM H/D abundances

- Cold HD (T<50K) is a proxy for cold molecular Hydrogen

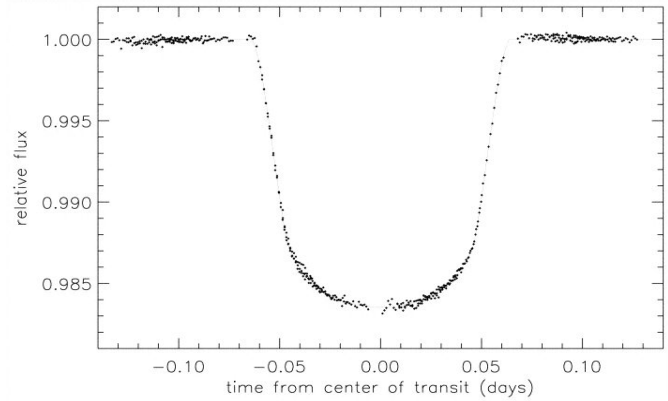
EXES and Comets: Gas Phase Constituents



- ***Production rates of water and other volatiles***
- ***Water (H_20) H_2 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 (CH_4)***
- ***Only SOFIA can make these observations near perihelion***

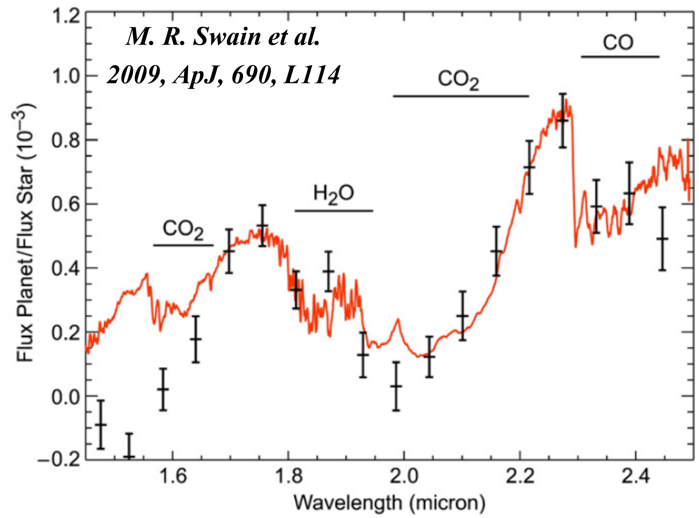


SOFIA and Extra-solar Planet Transits



HD 209458b transit with

HST STIS



HD 189733b

- *SOFIA flies above the scintillating component of the atmosphere where it can observe transits of planets across bright stars at high signal to noise*
- *Spectroscopic observations may be able to reveal the presence of biogenic molecules in the atmosphere - feasibility studies are yet to be conducted*

Summary

- *SOFIA will be a premier facility for far-IR and submillimeter spectroscopy for many years*

- *It will be especially effective for studies of the physics and chemistry of many stages in the process of stellar evolution:*
  - *Regions of star formation and ISM clouds*
  - *Luminous young stellar objects*
  - *Proto-planetary disks*
  - *Comets and planetary atmospheres*
  - *The winds of evolved stellar systems*

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