OPENING A NEW WINDOW ON OUR ORIGINS
WITH SOFIA-HIRMES

Klaus Pontoppidan
Space Telescope Science Institute
On behalf of the HIRMES team

SOFIA teletalk 2019
11 December 2019
<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
<table>
<thead>
<tr>
<th>Topic</th>
<th>Date</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument Overview</td>
<td>4 December</td>
<td>Matt Greenhouse</td>
</tr>
<tr>
<td>Protoplanetary Disks</td>
<td>11 December</td>
<td>Klaus Pontoppidan</td>
</tr>
<tr>
<td>Comets</td>
<td>15 January</td>
<td>Stefanie Milam</td>
</tr>
<tr>
<td>Deuterium in Giant Planets</td>
<td>29 January</td>
<td>Gordon Bjoraker</td>
</tr>
<tr>
<td>Debris Disks</td>
<td>5 February</td>
<td>Christine H. Chen</td>
</tr>
</tbody>
</table>
Most planets likely form within 10-20 AU

Zhang et al. 2018
The compositions of planets depend on their birth location.
The transport of volatiles can also change composition

VLT SPHERE – micron dust/gas

ALMA/DSHARP – mm dust
Planet-forming disks have different regimes of volatiles

- Warm water vapor (3-30 micron)
- Snowline (30-100 micron)
- Midplane ice (40-1000 micron)
- Photo-evaporated cold water vapor (179.5 + 538 micron)

* Not to scale
Bulk composition of gas and dust tends to be traced in IR.

Based on the standard TT ProDimo Model (Woitke et al. 2009)
The mass of planet-forming matter

The trail of water

The origins of life’s elements
[X/CO]
[X/dust]
\[ \frac{X}{(H_2 + H)} \]?
Classical mass tracers, CO and dust, underestimate mass mass

Ansdell et al. 2016
Hydrogen deuteride as a better mass tracer


Trapman et al. 2017
HD disk mass is a synergy between ALMA and a FIR facility.

Any molecule from ALMA/JWST

- HD $\rightarrow$ robust tracer of H$_2$
- J=1-0 at 112 micron
- We detected HD in 3 disks with Herschel-PACS
- The HD line is temperature dependent
- Requires good models of disk temperature
The trail of water

Mid-infrared (Spitzer)

Normalized flux + offset (mJy)

Very low-mass

C\(^{18}\)O, HCN

USCOCTIO33 (M4)

SCHJ0439 (M6)

AATau (K7)

RN090 (C5)

HD163296 (A0)

LkHa348 (B1)

Far-infrared (Herschel)

\(\alpha\)-H\(_2\)O \(7_{25} 6_{34}\)

\(\alpha\)-H\(_2\)O \(3_{21} 2_{12}\)

Figure credit: Andrea Banzatti

Combining Spitzer and Herschel-PACS detected surface snow lines

![Graph showing model surface and midplane snowlines against total luminosity.](image)

Zhang+, 2013
Blevins+ 2016
JWST will create a census of terrestrial planet-forming chemistry.

Lowest $H_2O$ energy available to JWST: $\sim 800$ K
Classical methods to detect ice in disks

Ices in a Protoplanetary Disc
NASA / JPL-Caltech / K. Pontoppidan [Leiden Observatory]

Spitzer Space Telescope • IRS
ESO • VLT • ISAAC
ssc2004-20c
Water ice emission using FIR phonon modes

Min et al. 2017

HD142527

Dependence on ice/rock ratio

Kamp et al. 2017
63 micron [OI] as a tracer of disk gas thermal balance

Alonzo-Martinez et al. 2017
• Provide Herschel-PACS line sensitivity
• at high spectral resolving power
• (R=50,000-100,000)
• cover unexplored region between Spitzer and Herschel
• increase spectral mapping speeds
Line tomography as an independent measure of abundance distributions
Value of resolving power
Transmission from the stratosphere

HD 1-0 transmission

H$_2$O Line Flux vs. Upper Level Energy at -30.0 km / s

- ortho H$_2$O
- para H$_2$O
The graph demonstrates the line flux in units of W/m² as a function of wavelength in micrometers (μm). The x-axis represents the wavelength range from 30 to 200 μm, while the y-axis shows the line flux ranging from $10^{-18}$ to $10^{-16}$ W/m².

Key features include:

- **H₂O 29 micron**: A peak in the line flux at a wavelength of 29 microns, indicated by a star and labeled as H₂O.

- **[OI]**: Another peak labeled as [OI] at a wavelength of 60 microns.

- **Science margin**: A designated area indicating the science margin.

- **5 sigma/1 hour Unresolved lines**: An area marked with 5 sigma and 1 hour, representing unresolved lines.

- **HD 1-0**: A peak in the graph labeled as HD 1-0.

Legend:
- PACS B3A
- PACS B3B
- PACS R1
- HIRMES MDLF (CBE)
Comparison with existing HD detections
The HIRMES sensitivity is achieved by...

Richards et al. 2018
Barrentine et al. 2018
Brown et al. 2018
Miller et al. 2018
Douthit et al. 2018
Planned legacy science investigation

- For the community
- No proprietary time
- Lots of remaining potential for GO programs

1. **HD**: measure disk masses, needed by ALMA+JWST studies of the same disks
2. **Water vapor**: locate inner disk molecular gas observed by JWST
3. **Water ice**: measure ice/rock ratio in ALMA+JWST selected disks
4. **Oxygen**: measure energy balance/critical input to thermochemical models
Available protoplanetary disk targets

![Graph showing available protoplanetary disk targets with different categories represented by colored bars. The categories include PP disk HD, PP disk [OI], PP disk H2O, and PP disk ice. The x-axis represents the logarithm of the signal-to-noise ratio, while the y-axis represents the number of candidate targets.](image-url)
High-resolution of HIRMES observations of TW Hya

18 km/s scan, 4 hours

36 km/s scan, 6 minutes
Low-resolution simulations of ice

HD 142527

1 hours, 9 grating settings

TW Hya

43 mu crystalline ice

3 hours, 4 grating settings
Summary of future infrared disk spectroscopy

- JWST NIRSpec+MIRI inner disk surface water+organics + atomic disk wind
- HIRMES line SED of water vapor at a wide range of temperatures
- ALMA imaging of cold gas
- HIRMES HD gas mass
- HIRMES measurement of bulk ice mass and cold dust composition

Flux density [Jy] vs Wavelength [μm]

- H₂O bending vibration
- CO fundamental
- Silicate
- HCN + C₂H₂
- O rotational spectrum
- O-H₂O ground-state
- "538 μm"