Submillimeter Wavelength Astronomy From Space

The spectral lines due to water and molecular oxygen dominate the opacity of the Earth's atmosphere at millimeter and submillimeter wavelengths. Water lines at 183, 325, 380, 448, 557, 752, 988, 1113 ... GHz and O₂ lines at 56, 58, 62, 119 ... GHz. Strong water lines 557, 752 and 988 GHz are pressure broadened and make ground-based submillimeter observations difficult.

“Windows”: 3, 2, 1.2, 0.85, 0.74, 0.45 & 0.35 mm
Atmospheric opacity has two detrimental effects:

1.) Reduces the signal strength: \( T_A = T_A^* e^{-\tau} \)

2.) Adds noise (thermal emission from atmosphere, \( T_{atm} \sim 250 \text{ K} \))

\[
V(\text{obs}) = \alpha \, G \, k \, [T_N + T_A + T_{atm} \, (1 - e^{-\tau})] \, \Delta \nu
\]

Why are submillimeter wavelengths important?

**Continuum:** SED of dust emission allows for better determination of the emissivity index, dust temperature and dust mass (in general dust emission is optically thin at submillimeter wavelengths).

Using templates, can determine the photometric redshift of distant 'submillimeter galaxies.
Spectral Lines: There are numerous spectral lines in the submillimeter


Examples:

- Higher rotational transitions of simple molecules studied at millimeter wavelengths (CO, HCN, CS ...) - probe hotter and denser gas (although spectrum dominated by asymmetric top molecules (CH3OH, .....)
- Hydrides – rotational lines of OH, CH, NH .... and HD
- Oxygen bearing molecules – H2O, O2, H3O+ ..... 
- Atomic Fine Structure Lines – Cl, CII, OI, NII .... (major coolants of ISM)
- Tracers of ion-molecular chemistry – H3+, H2D+ .....
Submillimeter Wave Astronomy Satellite (SWAS)
SWAS: Science Questions

• What is the composition of interstellar gas clouds?
  – Oxygen is the most abundant heavy element in the Universe. By observing molecular oxygen and water vapor, SWAS will determine the dominant reservoirs of oxygen in molecular clouds. This provides a crucial test of astrochemical models.

• How do interstellar gas clouds cool as they collapse to form new stars?
  – Molecular oxygen and particularly water vapor are potentially important coolants of interstellar gas clouds. If these molecules are present in high abundance, their infrared and submillimeter emissions would radiate away energy, thereby allowing cloud cores to cool and form new stars.

• Did interstellar processes create the water now present in the solar system?
  – Interstellar production of water vapor may have been followed by “freeze-out” onto dust grains and incorporation into the protosolar nebula.

• What is the large-scale distribution of CI and high-J $^{13}$CO in molecular clouds?
  – CI and high-J $^{13}$CO intensities and distribution are sensitive to the cloud structure.
### SWAS Spectral Lines

<table>
<thead>
<tr>
<th>Species</th>
<th>Transition</th>
<th>Upper Level Energy Above Ground-State (E/k)</th>
<th>Frequency (GHz)</th>
<th>Wavelength (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>3,3 - 1,2</td>
<td>26 K</td>
<td>487.249</td>
<td>615.276</td>
</tr>
<tr>
<td>Cl</td>
<td>³P₁ - ³P₀</td>
<td>24 K</td>
<td>492.162</td>
<td>609.134</td>
</tr>
<tr>
<td>¹³CO</td>
<td>J = 5 - 4</td>
<td>79 K</td>
<td>550.926</td>
<td>544.161</td>
</tr>
<tr>
<td>H₂O</td>
<td>₁₁₀ - ₁₀₁</td>
<td>27 K</td>
<td>556.936</td>
<td>538.289</td>
</tr>
<tr>
<td>H₂¹⁸O</td>
<td>₁₁₀ - ₁₀₁</td>
<td>26 K</td>
<td>547.676</td>
<td>547.390</td>
</tr>
</tbody>
</table>

Species/Transitions in red denote ground-state transitions.
A Small Explorer for the Submillimeter Region

- SWAS is a complete radio astronomy observatory in space
  - 54 x 68 cm primary mirror provides ~ 4 arcmin beam size
  - Dual heterodyne receivers simultaneously target five spectral lines in the 538 – 609 micron region at high spectral resolution (≤ 1 km/s)

- First space observatory to carry out pointed observations at submillimeter wavelengths

- Dedicated to the spectroscopic study of star formation and interstellar chemistry

- Provides our first opportunity to study cold water vapor and molecular oxygen in star-forming interstellar gas clouds
SWAS is a Complete Radio Observatory in Space

1) Off-Axis Cassegrain Telescope
   - 68 x 54-cm aperture
   - 3.3 x 4.5 arcmin. beam (553 GHz)
   - 3.5 x 5.0 arcmin. beam (490 GHz)

2) Submillimeter Heterodyne Receivers
   - Two receivers: 490 & 553 GHz
   - Passively-cooled to 175 K

3) Backend Spectrometer (AOS)
   - Observe all lines simultaneously
   - Velocity resolution of 1 km/s

4) Pointing
   - 3-axis stabilized
   - 5″ absolute pointing
   - 3-5″ pointing stability
SWAS Observes $\text{H}_2\text{O}$ in Comet Lee

- Observation of water vapor provides a more direct measurement of cometary $\text{H}_2\text{O}$ production rate than the more commonly used $\text{OH}$ molecule.

- For Comet Lee, SWAS was capable of detecting $\text{H}_2\text{O}$ after perihelion while during this period $\text{OH}$ was below the threshold for detection.
Water (H$_2^{16}$O) in Jupiter & Saturn
SWAS detected water in most galactic molecular clouds observed (the exception being the very cold clouds with $T < 10$ K)

Critical density of water quite large, also since it is a resonance line, prone to self-absorption.
Water abundance measured by SWAS orders of magnitude below chemistry predictions!!
Gas-phase chemistry of oxygen:

- $\text{OH}^+$ \xrightarrow{H_2} \text{H}_2\text{O}^+$ \xrightarrow{H_2} \text{H}_3\text{O}^+$
- $\text{H}_3^+ \xrightarrow{\text{H}_2} \text{OH}$ \xrightarrow{\text{e}^-} \text{O}_2$
- $\text{OH} \xrightarrow{\text{C, C}^+} \text{CO}$ \xrightarrow{\text{e}^-} \text{H}_2\text{O}$

Grain-surface chemistry of oxygen:

- $\text{O} \xrightarrow{\text{grain}} \text{O}_{\text{ice}} \xrightarrow{\text{H}} \text{OH}_{\text{ice}} \xrightarrow{\text{H}} \text{H}_2\text{O}_{\text{ice}}$
- $\text{OH}_{\text{ice}} \xrightarrow{\text{d}} \text{OH}$ \xrightarrow{\text{d}} \text{H}_2\text{O}$
Model including both gas-phase and grain-surface oxygen chemistry as a function of depth in cloud. Near surface, water photo-dissociated, deeper into cloud competition between desorption processes (thermal, photo and cosmic-ray) and O-freeze out (Hollenbach et al, 2009, Ap.J., 690, 1497)

Most of the oxygen is locked up in water ice on grain mantles.
O$_2$ not detected (note O$_2$ scaled by a factor of 10)
Water in Orion

HST Picture of Orion

SWAS Water Map of Orion

SWAS Water Spectra in Orion

$\text{H}_2\text{O}$
Water is the most abundant molecule behind moderate shocks.

Gas temperature behind a 10-20 km/s shock is of order 1000 K.

Water signature is persistent.

SWAS Observations of Water in Outflows

Franklin et al. (2008), Ap.J., 674, 1015
Evidence for hot gas with large water abundance. These spectra not velocity resolved.
Herschel Mission

- 3.5 m primary
- Orbit at L2 (launched with Planck)
- Telescope passively cooled to 70-90 K
- Instruments are cooled with superfluid He
- Coolant lifetime > 3 years
- Launch planned for May 6th
Herschel Instruments:

PACS
SPIRE
HIFI

Height: 9 m (29.53 ft)
Width: 4.5 m (14.76 ft)
Launch mass: 3300 kg (7275.25 lbs.)
Power: 1 kW
Launch vehicle: Ariane 5
Orbit: Lissajous around L2
Science data rate: 100 kbps
Telescope diameter: 3.5 m (11.48 ft)
Telescope WFE: 10 µm (goal 6 µm)
Telescope temperature: 70-90 K (-334° F to -298° F)
Abs pointing (68%): <3.7" (goal <1.5")
Rel pointing (68%): <0.3" (goal <0.3")
Helium II temperature: < 1.65 K (-456.7° F)
Lifetime in L2 (spec): > 3 yrs
**Photodetector Array Camera and Spectrometer (PACS)**

**Imaging Photometer:** Two-bands simultaneously (blue and red)

- **Blue:** 64x32 pixel array with 3.2” pixels, filters for 60-85 μm or 85-130 μm
- **Red:** 32x16 pixel array with 6.4” pixels, filter for 130-210 μm
- **Sensitivity:** 3 mJy (5-sigma in one hour)

**Integral Field Spectrometer:** simultaneous 55-105 μm & 105-210 μm spectroscopy

- **47”x47” FOV** arranged on two 16x25 detector arrays with image slicer
- **λ/Δλ=1000-5000**
- **Point source line sensitivity:** 4-10x10⁻¹⁸ W/m² (5-sigma in one hour)
Spectral and Photometric Imaging Receiver (SPIRE)

**Imaging Photometer:**

Simultaneous observations in 3 bands:
- 250 μm (139 pixels), 18” resolution
- 350 μm (88 pixels), 25” resolution
- 500 μm (43 pixels), 36” resolution

Point Source Sensitivity:
- 1.8, 2.2, 1.7 mJy (5-sigma in one hour with a 7-point jiggle map)

**Imaging Fourier Transform Spectrometer:**

Wavelength range: 194 – 324 and 315 - 672 μm
- number of imaging pixels: 37 and 19
- resolution 16” and 34”

λ/Δλ = 40, 160, or 1000 at 250 μm

Point Source Line Sensitivity:
- 2-4 x10^{-17} W/m² (5-sigma, one hour at highest spectral resolution)
Heterodyne Instrument for the Far-Infrared (HIFI)

*Seven heterodyne receivers* (dual-polarization):

**SIS Technology:**
- Band 1  0.48-0.64 THz (625-468 μm)
- Band 2  0.64-0.80 THz (468-375 μm)
- Band 3  0.80-0.96 THz (375-312 μm)
- Band 4  0.96-1.12 THz (312-268 μm)
- Band 5  1.12-1.27 THz (268-236 μm)

**HEB Technology:**
- Band 6 and 7  1.41-1.91 THz (213-157 μm)

Diffraction-limited resolution (12-47”)

Sensitivity: Near-quantum noise limit < 3 hν/k

**Spectrometers:**

- **WBS:** AOS spectrometer, 4x4 GHz, with resolution of 1.1 MHz
  \[ \lambda/\Delta\lambda = 10^6 \] (0.6 km/s resolution at 0.48 THz)

- **HRS:** Digital Autocorrelator spectrometer, 2 GHz maximum bandwith, with resolutions of 140 kHz, 280 kHz, 560 kHz and 1.1 MHz,
  \[ \lambda/\Delta\lambda = 107 \] (0.08 km/s at 0.48 THz)
Stratospheric Observatory for Infrared Astronomy (SOFIA)

Airborne observatory (Boeing 747)
2.5-m primary
Instruments can be changed
1000 hours of science per year

Altitude roughly 39,000-45,000 feet

Initial Facility Instruments:

- Faint Object Infrared Camera for the SOFIA Telescope (FORCAST)
  Mid-IR camera for 4-8, 16-26 μm and/or 25-40 μm (two 256x246 detector arrays)

- German Receiver for Astronomy at Terahertz Frequencies (GREAT)
  Heterodyne spectrometer covering 158-187, 110-125, and 63 μm
  $\lambda/\Delta\lambda = 10^6$ or $10^8$
Suite of Future PI Instruments (those at submillimeter):

HAWC: Bolometer Camera (12x32 pixels) covers 40-300 μm

FIFI LS: Imaging Spectrometer (two 16x25 pixel arrays covers with 42-110 and 110-210 μm), Grating spectrometer with $\lambda/\Delta\lambda = 1700$

CASMIIR: Heterodyne Spectrometer covering 250-600 μm spectral resolution of $\lambda/\Delta\lambda = 10^6$

SAFIRE: Imaging Fabry-Perot Bolometer Array Spectrometer covering 145-655 μm spectral resolution of $\lambda/\Delta\lambda = 1000-2000$

Schedule:
- Summer/Fall 2009 – First doors open flight
- Fall/Winter 2009 – Short Science Projects
- Summer 2010 – Basic Science Observations
Ground-Based Submillimeter Telescopes:

**Caltech Submillimeter Observatory (CSO)**
10-m telescope on Mauna Kea
Heterodyne: 230, 345, 450, 690 & 850 GHz bands
Continuum: SHARC II 384-pixel bolometer camera for 350, 450 & 850 μm and Bolocam a 115-pixel bolometer camera for 1100 & 2100 μm.

**James Clerk Maxwell Telescope (JCMT)**
15-m telescope on Mauna Kea
Heterodyne: 230, 345 and 690 GHz bands and HARP 16-pixel 345 GHz array
Continuum: SCUBA2 5120-pixel bolometer camera for 850 and 450 μm

**Submillimeter Telescope (SMT)**
10-m located on Mt. Graham, Az
Heterodyne: 230, 345 & 690 GHz bands

**Atacama Submillimeter Telescope Experiment (ASTE)**
10-m located in the Atacama, northern Chile
Heterodyne: 345 GHz band
Continuum: AzTEC
Ground-based Submillimeter Interferometers:

**Atacama Pathfinder Experiment (APEX)**
12-m telescope at the Atacama
   Heterodyne:  230, 350, 450 & 1300 GHz bands
   Continuum: LABOCA a 295-pixel bolometer array at 850 μm

**Submillimeter Array (SMA)**
Eight 6-m antennas located atop Mauna Kea
Baselines ranging from 8 to 509 m
Receivers for 230, 345 & 690 GHz.

**Atacama Large Millimeter Array (ALMA)**
Primary Array:  50 12-m antennas with 2016 baselines
Compact Array: 4 12-m and 12 7-m antennas with 120 baselines
Baselines ranging from 15 to 16,000 m
Frequencies:  84-950 GHz