SOFIA observations of far-infrared hydroxyl emission toward classical ultracompact HII/OH maser regions

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Outline

• Why to care about OH emission?
  • One of the first molecules detected in the radio: OH
  • The OH molecule can constrain the H$_2$O chemistry
• Rotational lines of OH: in the far-IR - compared to Herschel/HIFI, SOFIA/GREAT reaches higher frequencies with good spectral resolution: *unexplored territory*
• OH observations in SOFIA Early Science
• Models: envelope models (RATRAN), OH radio lines (Cesaroni & Walmsley 1991 model)
• Conclusion of the Early Science project
• Outlook: OH observations from Cycle I
Radio lines of OH

- **OH**: first interstellar molecule detected at radio wavelengths (Weinreb et al. 1963)
- “18 cm radio lines” of OH identified (Weinreb et al. 1965)
- radio interferometry:
  - origin: maser spots (0.’05)
- Hyperfine structure (HFS) transitions from higher rotational levels have also been detected (4 to 23 GHz)

(first OH lines observed)

Cesaroni & Walmsley (1991)
Radio lines of OH: anomalous HFS ratio

- Radio HFS lines of OH are not in LTE
  - anomalous HFS ratio
  - emission and absorption
  - stimulated emission (masers)
- Very high critical density ($n>10^8 \text{ cm}^{-3}$)
- Transitions between the HFS levels are sensitive to the far-IR radiation field, and the density
  - sensitive tracers of the physical conditions
- Excitation mechanism not well understood

**Fig. 2.** OH spectra obtained toward 10 positions in W51. The red, green, blue, and magenta curves show the 1612, 1665, 1667, and 1720 MHz transitions. The Doppler parameter $b_{718}$ at a velocity shift of 1.5 km s$^{-1}$ is defined (as usual) such that the optical depth can be straightforwardly obtained as 1. For lines of small optical depth, the equivalent width $W$ is related to the OH column density and the excitation efficiency—including atmospheric losses, as determined from calibration observations of an astronomical continuum source—and a cloud. The continuum brightness temperatures are measured equivalent width $W(v)$ of the radiation incident on the AO continuum source—and a cloud. The continuum brightness temperatures is 3.4 km s$^{-1}$ corresponding FWHM obtained from a Gaussian fit to the absorption line depth drops by a factor of 1.5, a Doppler parameter $b_{10}$ of 13.2.

The continuum brightness temperature is defined as $T_B = T_{CMB} + T_A$, where $T_A$ is the antenna temperature, $T_{CMB}$ is the temperature of the cosmic microwave background radiation (which is "chopped out" by the telescope beam—and an active feedback system, so that a negative value of $T_A$ is expected in LTE for $T_{CMB}$). For lines of small optical depth, the equivalent width $W$ is related to the OH column density and the excitation efficiency—including atmospheric losses, as determined from calibration observations of an astronomical continuum source—and a cloud. The continuum brightness temperatures are measured equivalent width $W(v)$ at 1612 MHz. In particular, the 1665/1667 MHz absorption strength was largest. Because of strong radio frequency interference, the 1720 MHz line strength could be measured reliably only toward the (0, 0) position, indicating the presence of weak maser activity. The 1720 MHz line is observed in emission toward the $^{13}$C$\text{C}^2\text{H}$ rotational state of water is very small, and thus the e-folding scale of the density is 2. The Doppler parameter $b_{10}$ for water is 3, the implied total water column density is 2$^{10}$ cm$^{-3}$.

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Excitation conditions of OH

- Two ladders:
  - different mechanisms are important for masing
    - $2\Pi_{1/2}$ ladder: collision
    - $2\Pi_{3/2}$ ladder: radiation
- maser emission in $2\Pi_{3/2}$ ladder: radiative excitation + collisional de-excitation
- far-IR line overlap + radiative pumping: problematic to models
- Cesaroni & Walmsley (1991): OH models revisited
- ultimately $N(OH)$ and $X(OH)$ is constrained
OH is chemically related to water

- The hydroxyl radical (OH) is closely linked to H₂O
- formation and destruction:
  \[ \text{OH} + \text{H}_2 \leftrightarrow \text{H}_2\text{O} + \text{H} \]
- byproduct of the H₂O photodissociation process in the presence of UV photons.
- OH can constrain the water chemistry
- important cooling line of the ISM (among [O I], [C II], CO, H₂O)
- constrain the cooling budget of shocks
Observations of the rotational lines of OH

- First observations of the far-IR OH lines: KAO and ISO
- Herschel/PACS
- But...OH is detected in various environments: maser spots, envelopes, shocks
  ➞ the line profile needs to be spectrally resolved to distinguish between broad/narrow component
  ➞ the HFS lines to study LTE conditions
- Herschel/HIFI: first spectrally resolved OH lines (163.1 µm)
- OH/H₂O ratio: constrain chemistry

Wampfler et al. (2011)

broad + narrow component: outflow+envelope origin
Motivation

- $2\Pi_{1/2} (J=3/2-1/2) \, \text{at} \, 1834.75 \, \text{GHz}$
  - @ 1837.82 GHz
- Targets: (ultra) compact HII regions
  - W3(OH)
  - NGC7538 IRS1
  - G10.62-0.39
- (ultra) compact HII: young and compact sources of radio free-free emission, but still embedded in a dusty envelope
- Goal: combined with radio cm transitions the physical conditions can be constrained

\[ E (\text{cm}^{-1}) \]
\[ E (\text{K}) \]

Cesaroni & Walmsley (1991)
Typical UC-HII regions: W3(OH)

- W3 Giant Molecular Complex (*Herschel*)
- W3(OH) at high angular-resolution:

Rivera-Ingraham et al. (2013)

\[ d = 2 \text{ kpc} \]
Typical UC-HII regions: NGC 7538

- NGC 7538 complex
- NGC7538 IRS 1 source: radio emission from ionized, collimated jet (HCHII region) + dust cores

The targeted sources probe the latest stage of the early evolution of high-mass (proto)stars

$d=2.7\,\text{kpc}$

Fallsheer et al. (2013)

$\text{G111}$

IRS 1-3

IRS 11, NGC 7538S

$\text{N}$

$10\,\text{pc}$

Spherical Accretion

Quenched (Nonexistent HII)

Bipolar Outflow

Spherical Outflow

Sandell et al. (2009), Zhu et al. (2013)
SOFIA/GREAT spectra – W3(OH)

- SOFIA/GREAT: DSB receiver ⇒ both the 1837 and 1834 GHz lines can be recorded!
SOFIA/GREAT spectra – NGC7538 IRS1, G10.62-0.39

The upper panel shows the 1H$_2$O emission feature at various velocities for NGC 7538 IRS1. The dashed line represents the position of the hf lines, and the green line indicates the position of the hf lines. The gray dashed line shows the position of the hf lines. The lower panel shows the 1H$_2$O emission feature at various velocities for G10.62-0.39. The dashed green line shows the position of the hf lines. The gray dashed line shows the position of the hf lines.
OH line parameters

- Gaussian line profiles
- HFS fit to the spectra in CLASS:

| Source          | Position   | $T_{mb,RJ}$ [K] | $v_{lsr}$ [km s$^{-1}$] | $\Delta v$ [km s$^{-1}$] | Total $\tau$ | $T_{ex}$ [K] |
|-----------------|------------|-----------------|--------------------------|--------------------------|--------------|--------------|
| W3(OH)          | 02:27:03.90 61:52:24.6 | 1.83 ± 0.34 | −45.70 ± 0.31 | 7.54 ± 0.87 | 0.1–2 | 40.2–5.1 |
| G10.62−0.39     | 18:10:28.64 −19:55:49.5 | 1.34 ± 0.29 | −3.17 ± 0.51 | 9.50 ± 1.15 | 0.1–5 | 30.2–3.7 |
| NGC7538 IRS1    | 23:13:45.36 61:28:10.5 | 1.04 ± 0.34 | −57.80 ± 0.43 | 5.46 ± 1.00 | 0.1–5 | 24.1–3.5 |

- S/N of the data allows a rough estimate of these parameters
- Line parameters consistent with Plume et al. (1997)
  ⇒ origin of dense turbulent medium
- presence of a broad component? < 0.4 K
- 2.5 THz line observed in absorption towards NGC7538 IRS1
Models: NGC7538 IRS 1

- OH: very high critical density
  ➞ $n > 10^8 \text{ cm}^{-3}$, LTE may not apply
- Envelope model: RATRAN
  
  \textit{Hogerheijde} \\& \textit{van der Tak} (2000)

- Dust parameters:
  - $L = 1.3 \times 10^5 \text{ L}_\odot$
  - $n_0 = 5.3 \times 10^4 \text{ cm}^{-3}$; $p = -1.0$
  - $X(\text{OH}) = 0.8 \times 10^{-8}$
- RATRAN does not treat line overlap and overlap effects
- good fit to the observed lines!

\textit{OH emission in NGC7538 IRS1: well reproduced by an envelope model!}
Models: G10.6-0.39

- Envelope model: RATRAN

- Dust parameters:  
  - $L = 1.3 \times 10^5 \, L_\odot$
  - $n_0 = 5.3 \times 10^4 \, \text{cm}^{-3}$; $p = -1.0$
  - $X(\text{OH}) = 0.8 \times 10^{-8}$

- underestimating the observed lines
Models considering the radio lines

- the masing radio OH lines: transitions between the HFS levels are sensitive to the far-IR radiation field, effects of line overlap need to be considered

- Cesaroni & Walmsley (1991) LVG model:
  - far-IR radiation field
  - line overlap

- qualitatively explains the behavior of the radio lines
Models considering the radio lines

Cesaroni & Walmsley (1991)
models for W3(OH)
$T_{\text{dust}} = T_{\text{gas}} = 151$ K
internal dust+line overlap
$R=0.01$ pc
$200$ km s$^{-1}$ pc$^{-1}$
$X(\text{OH}) = 2 \times 10^{-7}$
Models considering the radio lines

- Cesaroni & Walmsley model: qualitatively reproduce the radio OH lines for W3(OH)
- Including far-IR radiation field: good correspondence to the observed line intensities at n~2-3 x 10^6 cm^{-3}
- Excluding far-IR radiation field: underestimating the line intensity
- Considering the envelope component (RATRAN): underestimates the line intensity

**OH emission in W3(OH): from the UCHII region and not the nearby hot-core, W3(H_2O)!
Conclusions

• the far-infrared rotational lines of OH detected $2\Pi_{1/2} (J=3/2-1/2)$
  -> both doublets spectrally resolved
• the $2\Pi_{3/2} (J=5/2-3/2)$ line is in absorption
• Models:
  • low OH abundance envelope: good for NGC7538 IRS 1
  • not sufficient for W3(OH) and G10.62-0.39
    ‣ additional high-density, high OH abundance component is needed
  • W3(OH): The emission from W3(OH) comes predominantly from the UCHIIIR and not from the hot core.
  • RATRAN modeling yields for the dense component $n(H_2)=\sim3\times10^6 \text{ cm}^{-3}$
  • accounting for pumping by the FIR radiation field emitted by hot dust is needed
Outlook

- More OH lines observed towards typical UC-HII regions
- Sources also observed with Herschel

| Source  | $2\Pi_{1/2}$ (J=3/2-1/2) 1837 GHz | $2\Pi_{3/2}$ (J=5/2-3/2) 2504 GHz |
|---------|----------------------------------|----------------------------------|
| G10.47  | ✓                                | ✓                                |
| G34.26  | ✓                                | ✓                                |
| W49N    | ✓                                | ✓                                |
| W49B    | ✓                                | ✓                                |
| W33A    | ✓                                |                                   |
| G332.83 | ✓                                | ✓                                |
Outlook

Next steps:

• Include the latest collisional rate coefficients in the Cesaroni & Walmsley model
• Calibrate the radio lines to the far-infrared rotational lines of OH
• derive OH abundances in the various components: envelopes, shocks and outflows
• Cycle I data: reduction and data analysis in progress...
