Molecules in Massive Protostars from the Near to Mid Infrared: Unique Constraints from SOFIA/EXES

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Based largely on results from...

Indriolo et al. 2015, ApJL, 802, L14

SOFIA/EXES Observations of Water Absorption in the Protostar AFGL 2591 at High Spectral Resolution

David Neufeld, Curtis DeWitt, Matt Richter, Adwin Boogert, Graham Harper, Dan Jaffe, Kristin Kulas, Mark McKelvey, Nils Ryde, & Bill Vacca
Massive Protostars

- Luminous central objects ($10^4 L_{\text{sun}}$)
- Deeply embedded within gaseous envelope
- High temperature chemistry
- Multiple kinematic components (envelope, disk, torus, jet, wind, outflow, infall)
- Large scale molecular outflows
Chemical Models


Simple models predict roughly half of the oxygen in CO and half in H$_2$O in the inner envelope. H$_2$O ice is abundant in outer envelope.
NIR Images

Not quite spherically symmetric

M. Goto 2013, private comm.  
CO Observations of AFGL 2591

CO in AFGL 4176

- CRIRES observations of $^{13}\text{CO}$ $\nu=1-0$ band
- Detections of $^{12}\text{CO}$, $^{13}\text{CO}$, C$^{18}\text{O}$, C$^{17}\text{O}$, and $^{12}\text{CO}$ $\nu=2-1$
- Currently under analysis by Agata Karska
**CO spectra are complicated**

- There are multiple velocity components absorbing in CO, all of which vary in different ways with rotational level.
- Difficult to decompose absorption features, especially with blends between isotopologues.
- We’d like a simpler tracer of the gas around protostars.
- Some possibilities: H$_2$O, C$_2$H$_2$, HCN.
Astrophysical Water

• $\text{H}_2\text{O}$ is difficult to observe in astrophysical objects due to Earth’s atmosphere (with the exception of masers)
Water Vibrational Bands

- $\nu_1$: symmetric stretch
  - 2.7 $\mu$m
- $\nu_2$: bend
  - 6.1 $\mu$m
- $\nu_3$: asymmetric stretch
  - 2.7 $\mu$m
Atmospheric Transmission

ATRAN (Lord 1992) simulated atmospheric spectrum at 14,000 ft with 2.5 mm PWV
Astrophysical Water

- **H$_2$O** is difficult to observe in astrophysical objects due to Earth’s atmosphere (with the exception of masers)

- Two options:
  - (1) target transitions not populated in atmosphere
  - (2) go above the atmosphere
Go Over (in wavelength)

\( \text{H}_2\text{O} \nu_1 \) and \( \nu_3 \)  \hspace{1cm} \text{H}_2\text{O} \nu_2 \hspace{1cm} \text{H}_2\text{O} \) rotational

23 May 2015
Water in AFGL 2136

- Massive protostar used as a background source searching for HF R(0) transition
- Atmospheric water lines show absorption wing
- Realized it’s coming from the protostar

data from CRIRES at VLT
Water in AFGL 2136

- 35 absorption features
- 47 transitions probing 44 unique levels

AFGL 2136 Rotation Diagram

- Well matched by single temperature LTE
Model with Radiative Transfer

- Statistical equilibrium analysis
- Accounts for radiative trapping
- Fair agreement with ISO results

\[ T = 500 \pm 200 \text{ K} \]
\[ N(\text{H}_2\text{O}) = (1.5 \pm 0.6) \times 10^{18} \text{ cm}^{-2} \]

- Improved with data probing levels at low/high energy

\[ T = 506 \pm 25 \text{ K} \]
\[ N(\text{H}_2\text{O}) = (1.02 \pm 0.02) \times 10^{19} \text{ cm}^{-2} \]
\[ n(\text{H}_2) > 5 \times 10^9 \text{ cm}^{-3} \]
Example $v_2$ & Rotational Transitions

- Archival TEXES data courtesy of John Lacy and Matt Richter
- $H_2O$ detected in absorption

- CRIRES observations targeting CO at 4.7 $\mu$m also cover water transitions
- Absorption profile best matches vibrationally excited $^{12}$CO
Go Over (the Atmosphere)

ATRAN (Lord 1992) simulated atmospheric spectrum at 43,000 ft with 0.01 mm PWV
ISO Observations (AFGL 2591)


\[ N(\text{H}_2\text{O}) = (3.5 \pm 1.5) \times 10^{18} \text{ cm}^{-2} \quad T = 450 \pm 200 \text{ K} \]

- Analysis relies on model fit assuming some Doppler parameter
HIFI Observations (AFGL 2591)

\[ N(\text{H}_2\text{O}) = \sim 4 \times 10^{13} \text{ cm}^{-2} \]

\[ T = 70 - 90 \text{ K} \]

Targeting AFGL 2591

- ISO observations show that source has 6 µm water absorption
- Know that it shows absorption from the $J_{K_aK_c} = 0,0$ and $1,1$ levels (ground para & ortho)
- Flux at 6 µm is 520 Jy
- Good target for EXES commissioning flight (Apr. 10, 2014), both with respect to location and Doppler shift
AFGL 2591 Region

- $JHK'$ image GemN
- 3.6 cm contours VLA
- Massive protostar is associated with source VLA 3

AFGL 2591 Region

- $JHK'$ image GemN
- 3.6 cm contours VLA
- Massive protostar is associated with source VLA 3
- Central source nodded along slit
- Subtract image pairs

Observing Setup

- Altitude: 43,000 ft
- Reference Wavelength: 6.1125 μm
- Slit: 1.9” × 9.9” (R~86,000; res~3.5 km/s)
- Exposure Time: 1134 s (42 at 27 s each)
- Standard Star: Vega (100 Jy @ 6μm)
  - Observed during flight leg 2 hr prior to science target, at comparable altitude and air mass
EXES vs ISO coverage

EXES Echellogram
EXES Echellogram
Extracted Spectrum (AFGL 2591)
Spectrum (AFGL 2591 & Vega)
Processed Spectrum

Intensity (Arbitrary Units)

Relative Intensity

Wavelength (µm)

23 May 2015
SOFIA/EXES AFGL 2591
Absorption Line Fitting

\[ I = I_0 \left[ 1 - f_c \left( 1 - \exp \left( -\tau_0 \exp \left( -\frac{(\nu - \nu_{\text{LSR}})^2}{2\sigma_v^2} \right) \right) \right) \right] \]

- Gaussian in optical depth
- Allows for fractional coverage of source by absorbing gas, \( f_c \)
Rotation Diagram (AFGL 2591)

Indriolo et al. 2015, ApJL, 802, L14
# Comparison of Analyses

<table>
<thead>
<tr>
<th>Instrument</th>
<th>$\text{H}_2\text{O}$ Column Density (cm$^{-2}$)</th>
<th>Temperature (K)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO-SWS</td>
<td>$(3.5\pm1.5)\times10^{18}$</td>
<td>450±200</td>
<td>Boonman &amp; van Dishoeck 2003</td>
</tr>
<tr>
<td>Herschel PACS</td>
<td>$\sim6\times10^{14}$</td>
<td>160±130</td>
<td>Karska et al. 2014</td>
</tr>
<tr>
<td>Herschel HIFI</td>
<td>$\sim4\times10^{13}$</td>
<td>70—90</td>
<td>Choi et al. 2015</td>
</tr>
<tr>
<td>SOFIA EXES</td>
<td>$(1.3\pm0.3)\times10^{19}$</td>
<td>640±80</td>
<td>Indriolo et al. 2015</td>
</tr>
</tbody>
</table>

- IR observations give both larger column densities and temperatures
- *Herschel* observations primarily probe transitions out of relatively low-energy states
Ground state with HIFI and EXES

- Rotational transition at 1113 GHz observed with HIFI (19” beam)
- Ro-vibrational transition at 6.1 μm observed with EXES
Ground state with HIFI and EXES

- Rotational transition at 1113 GHz observed with HIFI (19” beam)
- Ro-vibrational transition at 6.1 μm observed with EXES
- Vibrationally excited transition blend with ground state line
AFGL 2591 Region

- EXES slit in blue
- HIFI beam in red

EXES Advantages

- $\nu_2=1-0$, $1_{1,1}-0_{0,0}$ transition does not suffer significant interference from emission
- Multiple transitions may be observed simultaneously
- Narrow slit provides high resolution, and limits flux from surrounding region
What to do next?

- Target more massive protostars where water absorption is detected (SOFIA/EXES)
- Target massive protostars in NIR and MIR atmospheric windows from the ground to find other molecules (TEXES on Gemini N.; CRIRES+ on VLT, when refurbished)
- Utilize models more complex than simple absorbing slab
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Other Molecules in Protostars

- While CO and H$_2$O are certainly two of the most abundant species in protostars, many more molecules have been detected.
- HCN, C$_2$H$_2$, NH$_3$, HNCO, CH$_4$, HF, HCl
- All of these can provide important constraints on physical conditions.
Temperature Comparison

Inferred temperature changes with different molecules, and even with different observations of the same molecule (high vs. low resolution)
MIR Survey of NGC 7538 IRS 1

- TEXES/Gemini N. observations
- Detected species varies between protostars
- AFGL 2591 shows only HCN & C$_2$H$_2$

Knez 2006 (thesis)

GemN/TEXES Observations

- AFGL 2136 at 13 μm
- C$_2$H$_2$ and HCN ro-vibrational bands in absorption

- AFGL 2136 at 10.7 μm
- Several transitions of NH$_3$
AFGL 2136: HCl

- Trace species HCl seen in absorption (3.5 µm)
- Both $^{35}$Cl and $^{37}$Cl isotopologues
- Inferred gas properties:
  - $T=254\pm10$ K
  - $n>10^9$ cm$^{-3}$

Molecules Molecules Everywhere...

• Different molecules are indicating different physical conditions
• Possibly probing different locations
• Possibly saying something about radiative versus collisional excitation
Absorption in the Near-Mid IR

• In objects as complex as massive protostars, the emitting region must change significantly from 2 μm to 14 μm

• Unclear how exactly this effects observed molecular absorption across the near-mid infrared

• Certainly worth targeting the same species across this wavelength range
Current Status

- A wide variety of molecules have been detected in absorption in massive protostars
- Objects have generally been targeted in narrow spectral windows around lines of interest to observer
- There exists neither a uniform sample of spectra across many protostars, nor a “full” spectrum of a single protostar at high resolution
From the Ground

ATRAN (Lord 1992) simulated atmospheric spectrum at 14,000 ft with 2.5 mm PWV

\[\text{Transmission} \quad \text{Wavelength (\text{\textmu m})}\]

- \(\text{H}_2\text{O}\)
- \(\text{HF}\)
- \(\text{HCN}\)
- \(\text{C}_2\text{H}_2\)
- \(\text{H}_2\text{CO}\)
- \(\text{HCN, C}_2\text{H}_2, \text{H}_2\text{CO, H}_2\text{O, NH}_3\)

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SOFIA/EXES AFGL 2591
From the Stratosphere

ATRAN (Lord 1992) simulated atmospheric spectrum at 43,000 ft with 0.01 mm PWV
Future Work

• Design observations to target the same spectral window in a sample of protostars
• Select one or two objects for the purpose of performing full spectral scans
• SOFIA/EXES uniquely capable of doing this work at 6-8 μm