Probing the Hot, Dense Gas near Massive Protostars via Water Absorption

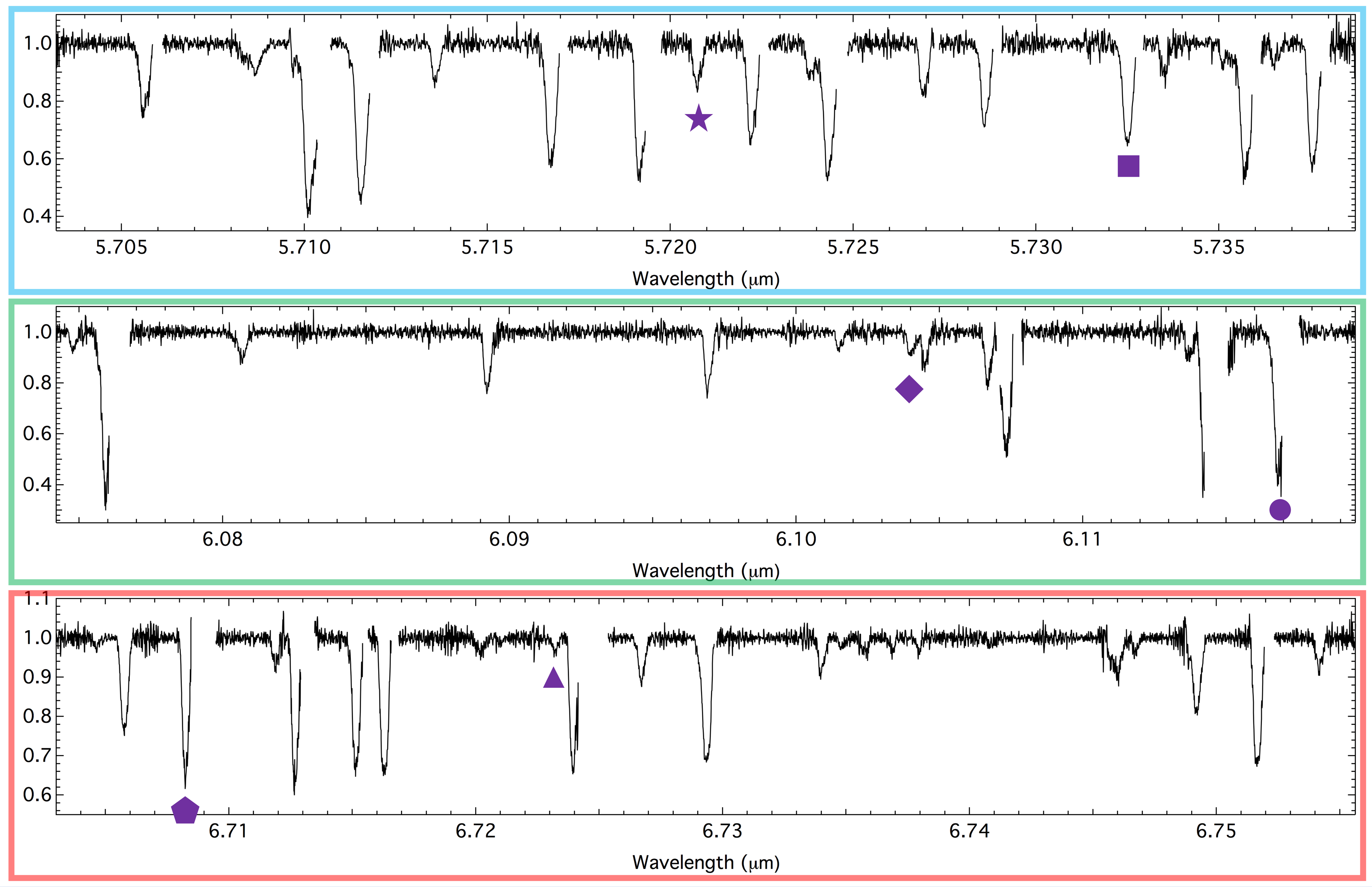
Nick Indriolo[1], A. C. A. Boogert[2], C. N. DeWitt[3], A. Karska[4], E. J. Montiel[5], D. A. Neufeld[6], & M. J. Richter[5]

[1]Space Telescope Science Institute, Baltimore, MD, USA
[2]Institute for Astronomy, University of Hawaii at Manoa, Honolulu, HI, USA
[3]USRA, SOFIA, NASA Ames Research Center, Moffett Field, CA, USA
[4]Nicolaus Copernicus University, Torun, Poland
[5]University of California, Davis, CA, USA
[6]Johns Hopkins University, Baltimore, MD, USA

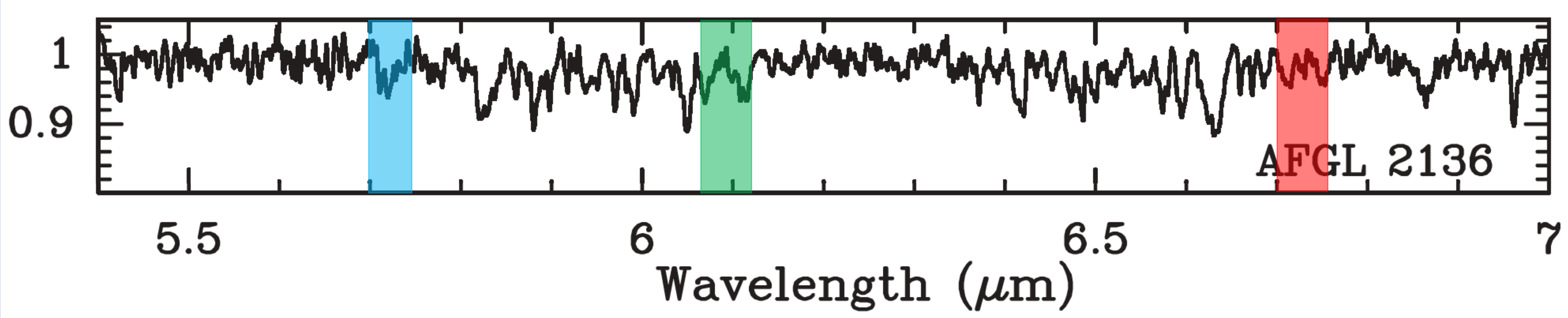
Background

- Warm conditions near massive protostars drive a significant fraction of oxygen into water vapor
- Ro-vibrational bands of H_2O are centered at about 3 μm and 6 μm, and cause the Earth's atmosphere to be mostly opaque at these wavelengths
- SOFIA (Stratospheric Observatory for Infrared Astronomy [7]) provides an observing platform above 99% of the water vapor in Earth's atmosphere
- EXES (Echelon-Cross-Echelle Spectrograph [6]) offers ~4 km/s spectral resolution in the mid-IR
- Previous observations of massive protostars in the mid-IR with ISO-SWS covered the full extent of the ν_2 vibrational band of H_2O, but at low spectral resolution (~200 km/s), such that absorption from several transitions is blended together (see spectrum below)
- High spectral resolution observations of H_2O can resolve individual absorption lines, which provides information about specific transitions and the rotational states they connect
- This enables the study of conditions (e.g., density, temperature, radiation field) surrounding massive protostars, as well as the kinematics of the absorbing gas (via line profiles)

SOFIA/EXES spectra of AFGL 2136



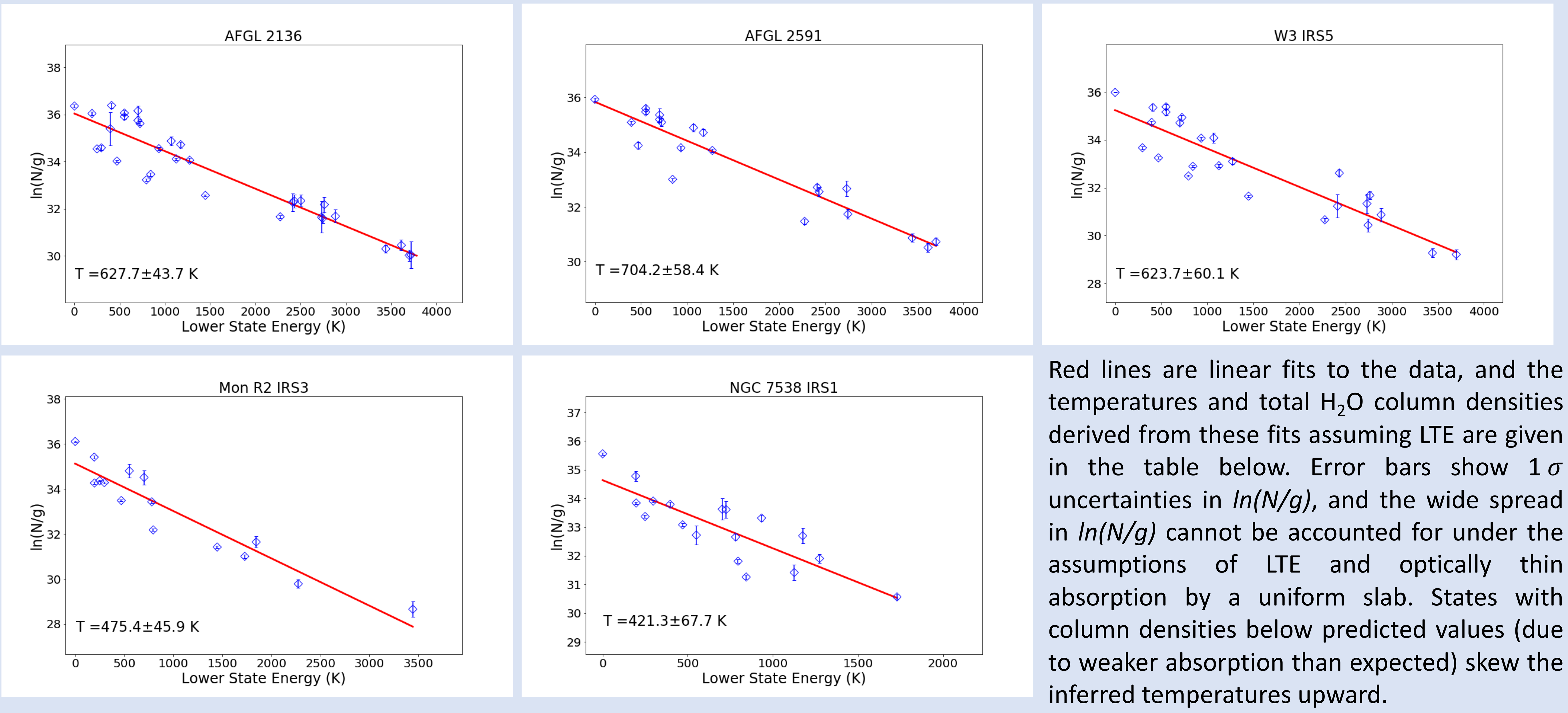
ISO-SWS spectrum of AFGL 2136



Left: ISO-SWS spectrum of the massive protostar AFGL 2136 covering the ν_2 vibrational band of H_2O [1]. The ~200 km/s spectral resolution results in blending of the absorption from different transitions. Shaded regions mark the wavelength ranges targeted by our SOFIA/EXES observations.

Right: SOFIA/EXES spectra of AFGL 2136, color-coded to match the corresponding shaded regions shown in the ISO-SWS spectrum. Absorption due to more than 50 different ro-vibrational transitions of H_2O is detected. Select transitions are marked and identified (see table below at right) to demonstrate the utility of high spectral resolution observations in probing rotational levels of H_2O over a wide range of energies and out of multiple vibrational states, and in revealing absorption from the $H_2{}^{18}O$ isotopologue.

H_2O Rotation Diagrams for Protostars Observed with SOFIA/EXES



Red lines are linear fits to the data, and the temperatures and total H_2O column densities derived from these fits assuming LTE are given in the table below. Error bars show 1σ uncertainties in *ln(N/g)*, and the wide spread in *ln(N/g)* cannot be accounted for under the assumptions of LTE and optically thin absorption by a uniform slab. States with column densities below predicted values (due to weaker absorption than expected) skew the inferred temperatures upward.

Select transitions observed toward AFGL 2136

Marker	Molecule	$v_2' - v_2''$	$J(K_a,K_c)' - J(K_a,K_c)''$	Lower State Energy (K)
●	H_2O	$1-0$	$1(1,1)-0(0,0)$	0
⬟	H_2O	$1-0$	$4(0,4)-5(1,5)$	470
■	H_2O	$1-0$	$8(3,6)-8(2,7)$	1274
★	H_2O	$2-1$	$10(1,10)-9(0,9)$	3615
▲	H_2O	$1-0$	$13(4,10)-13(5,9)$	3701
◆	$H_2{}^{18}O$	$1-0$	$3(2,1)-3(1,2)$	249

Summary

- SOFIA/EXES observations of massive protostars near 6 μm reveal a wealth of resolved H_2O absorption lines, including some from the $H_2{}^{18}O$ isotopologue
- Observations of H_2O in the mid-IR probe a different region around massive protostars than in the far-IR and THz regimes, as evidenced by the disparity in temperature and column density estimates
- Investigation into what causes several transitions to have weaker absorption than expected is ongoing.

Comparison of Inferred Properties to Previous Studies

Target	$N(H_2O)$	Temperature	Instrument &	$N(H_2O)$	Temperature	Instrument &	$N(H_2O)$	Temperature	Instrument &
	(10^{18} cm^{-2})	(K)	Reference	(10^{18} cm^{-2})	(K)	Reference	(10^{18} cm^{-2})	(K)	Reference
AFGL 2136	2.5±0.6	628±44	EXES [4]	1.5±0.6	500±200	ISO/SWS [1]	10.2±0.2	506±25	VLT/CRIRES [3]
AFGL 2591	2.4±0.6	704±58	EXES [4]	3.5±1.5	450±200	ISO/SWS [1]	4×10^{-5}	80±10	Herschel/HIFI [2]
Mon R2 IRS3	0.6±0.2	475±46	EXES [4]	0.5±0.2	250±150	ISO/SWS [1]	...	...	...
NGC 7538 IRS1	0.3±0.1	421±68	EXES [4]	<0.5	...	ISO/SWS [1]	$(2\pm1)\times10^{-4}$	170±70	Herschel/PACS [5]
W3 IRS5	1.1±0.4	624±60	EXES [4]	0.3±0.1	400±200	ISO/SWS [1]	$(6\pm4)\times10^{-4}$	220±160	Herschel/PACS [5]

References

1 – Boonman & van Dishoeck 2003, A&A, 403, 1003
2 – Choi et al. 2015, A&A, 576, A85
3 – Indriolo et al. 2013, ApJ, 776, 8
4 – Indriolo et al. 2019 (in preparation)
5 – Karska et al. 2014, A&A, 562, A45
6 – Richter et al. 2010, Proc. SPIE 7735
7 – Temi et al. 2014, ApJS, 212, 24