

The Spectral Legacy of the Herschel: A Summary of Results from the Herschel Observations of EXtra-Ordinary Sources Key Program

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Broad Perspective

- Stars are born in molecular clouds that exhibit a high degree of chemical complexity - clearly dominated by organics, water, carbon monoxide, and carbon dioxide
- How this complexity develops is uncertain -- gas phase? catalytic chemistry on grain surfaces?
- We have been hindered by our inability to view the entire spectrum of star forming gas -- cannot trace water and key coolants (e.g. C II, O I, CO ladder)
- How do organics and water form in space? How are these then delivered to the planet-forming disk and then to young planets?

Orion and Sgr B2: Extra-Ordinary Objects

- Contain THE CLASSIC EXAMPLES of phenomena found throughout the ISM
 - ➡ Hot Cores: Orion KL, Sgr B2 N
 - Photodissociation Region (PDR): The Orion Bar
 - ➡ Shocks: Orion KL
 - ➡ Diffuse gas in Milky Way: Sgr B2 M peers through the galaxy
- Main part of program:
 - Full HIFI spectral scans of Orion KL, Orion S, Orion Bar, Sgr B2 (M), Sgr B2(N)
 - PACS range scans of same sources
 - Water Maps of shock/deep integrations/search for large molecules



E. Bergin

Herschel and Spectral Surveys

Including ground based coverage Orion KL and Sgr B2 Spectrum: Most complete spectrum of molecular gas at high spectral resolution ever obtained.









Wang et al. 2011

Overlapping emission lines
Multiple line of sight components (outflow, warm and hot dense cores)
~1 million independent spectral channels

Spectral Data Mining

- Holistically characterize HIFI spectrum of Orion KL and Sgr B2 N
- Our analysis indicates ~2x10⁴ spectral features present in the Orion KL HIFI spectrum from over 30 molecules
- Each detected molecule/isotopologue needs to be modeled/ analyzed one at a time -- over the entire bandpass
- Divided the labor (molecules) among ~15 people led by Nathan Crockett (Orion KL) and Justin Neill (Sgr B2 N)
 - Each person modeled several molecules
- Analysis tools:
 - XCLASS LTE MADEX or RADEX LVG code

Currently Modeled Molecules Orion KL

Currently Modeled Molecules Orion KL

- NH₂CHO
- SiS
- C₂H₅OH
- H_2CS
- NO
- NS
- SO, ³⁴SO, ³³SO, S¹⁸O
- SO₂, ³⁴SO₂, ³³SO₂
- HCN, H¹³CN, HC¹⁵N
- HNC, $H^{15}NC$, $HN^{13}C$
- SiO
- CH₃CN, ¹³CH₃CN, CH₃¹³CN
- NH₃, ¹⁵NH₃, NH₂D
- HCl, H³⁷Cl
- H_2S , $H_2^{33}S$, $H_2^{34}S$
- H₂CO, H₂¹³CO, HDCO

- HCOOCH₃
- CCH
- CN
- HC₃N
- H₂O, HDO, HD¹⁸O, D₂O, H₂¹⁸O, H₂¹⁷O
- CH₃OH, ¹³CH₃OH, CH₃OD, CH₂DOH
- C₂H₅CN
- HNCO, HN¹³CO
- HCS⁺
- H₂CCO
- OCS
- CH₃OCH₃
- CS, C³⁴S, C³³S, ¹³CS
- CO, ¹³CO, C¹⁷O, C¹⁸O • HCO⁺

Example: HCOOCH₃

Complex organic with >1000 emissive transitions at HIFI frequencies Data - plotted in white LTE Model - single component: T=110K, N_{col} =1x10¹⁷cm⁻², v_{lsr} =8.0 km/s, Δv =2.5 km/s

consistent with the CR Increasing Elow

V_{lsr}(km/s) Crockett et al. 2013, ApJ, sub.

Example: HCOOCH₃

V_{lsr}(km/s) Crockett et al. 2013, ApJ, sub.

Example: HCOOCH₃

V_{lsr}(km/s) Crockett et al. 2013, ApJ, sub.

1.5 10⁶

equency (MHz)

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		¹³ CH ₃ CN		C₂H₅OH		60				
		³⁴ S0 ₂		CH ₃ OCH ₃		680				
		CH ₃ CN		СН _з ОСНО		40				
				CH ₈ OH	T _{MB}					
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•		NH ₂ CHO all molecules				0				
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/ 	$ \begin{array}{c} & \text{NH}_{2}CHO \\ & \\ & C_{2}H_{0}CN \end{array} \end{array} $ all molecules					0 5 1	0 5 10 ⁵ 10 Res			

CH₃OCH₃

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i ya	 ¹³ CH ₃ CN		C ₂ H ₅ OH	
	 ³⁴ SO ₂		CH ₃ OCH	
H	 CH₃CN		CH ₃ OCH	
₹ 0				
Z,	 SO ₂		OCS	
Z	 C ₂ H ₅ CN	all mol	ecules	

N. Crockett

Orion and Sgr B2 (N)

Sgr B2 - lines generally weaker than Orion

greater beam dilution and higher dust extinction

Strength of Wide Band Analysis

Neill et al. 2012

What do we get out of this?

Constrained the excitation -- sometimes with over 1000 lines

- Abundance on this scale is well determined *assuming a source size!*
 - multiple sources, high data fidelity, similar analysis
 - can be compared to models of organic synthesis
 - ➡ Have water!
 - templates for ALMA

Herschel and Organics

Detection of HD¹⁸O

six HD¹⁸O lines detected with V_{lsr} ~ 7 km/s - not typical
HDO must be optically thick in the component from which HD¹⁸O emits

• extreme D/H ratio or very high H₂O column

Analyzed with 37 HD¹⁶O, 20 H₂¹⁸O, and 16 H₂¹⁷O transitions

Neill et al. 2013

emission continuum HDO integrated 230 GH Contours: - -Color scale

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HDO with ALMA

- ALMA SV Date of Orion KL $(1.7'' \times 1.2'')$ spatial resolution)
- Brightest HDO emission in small clump (2") in size at 7 km/s
- Agrees with HD¹⁸O velocities
- Analysis of high-lying water isotopologue lines consistent with emission from this small clump
- \rightarrow N(H₂O) ~ 2 x 10²⁰ cm⁻² $D/H \sim 2 \times 10^{-3}$

Crazy Statistics

Herschel and Spectroscopy

- More cohesive molecular census
- New clues to organic origins
- New tracers of hidden radiation fields
- Strong constraints on molecular excitation with tens, hundreds, thousands of lines of individual species
- Isolation of a compact water factory in Orion
- New information extracted from molecular spectra
- Glimpse of a small portion of the wealth and legacy of Herschel Spectroscopy