Herschel/SPIRE Spectra of Seyfert Galaxies

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Outline

- Introduction
  - SPIRE/FTS and Sub-mm Spectra
- HF Absorption and Emission
- Mid-J CO Emission
  - LVG Models
  - PDR and XDR models
  - AGN vs Starburst
- Summary
Introduction
SPIRE-FTS

- Fourier Transform Spectrometer (FTS) on-board Herschel

- **SSW**
  - 925-1500 GHz
  - 195-325 μm
  - ~18 arcsec beam

- **SLW**
  - 450-950 GHz
  - 320-670 μm
  - ~30 arcsec beam

Spectral resolution 1.5 GHz   R ~ 300-1000
SPIRE-FTS

FTS footprint over SPIRE 250μm image

Spectrum central bolometer

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SPIRE-FTS sub-mm Spectrum

Ten mid-J CO ladder from $J = 4$-3 to $J = 13$-12
Two [CI] lines at 492 and 809 GHz
A few $\text{H}_2\text{O}$ and $\text{H}_2\text{O}^+$ transitions
$\text{CH}^+$ and $\text{OH}^+$ transitions
$\text{HF} J = 1$-0
$\text{[NII]}$ 1461 GHz (205 micron)

Molecular gas.

Ionized gas.
HF 1-0 1232 GHz
Hydrogen Fluoride

- F abundance is low $\sim 10^{-8}$

- $F$ forms $HF$ rapidly when $H_2$ becomes abundant

$$F + H_2 \rightarrow HF + H \text{ exothermic}$$

- $HF$ more abundant than $CO$ for $A_v < 1$ mag

PDR model Neufeld+2005
**HF 1-0 at 1232 GHz**

Expected in absorption

E$_{J=1}$ = 59 K & high critical density n$_{H_2}$ ~ 10$^{10}$ cm$^{-3}$ (at 50 K)

A$_{10}$ = 2.4 x 10$^{-2}$ s$^{-1}$

τ = 41 s

For comparison for CO 1-0

τ = 160 days and E$_i$ = 6 K

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Herschel detections of HF

Mrk 231 - Sy1
Spinoglio+2012

Arp220 - Starburst
Rangwala+2011

NGC1068 - Sy2
Spinoglio+2012

M82 - Starburst
Kamenetzky+2012
HF in Sy Galaxies

- 2 detections in our sample
  - UGC05101. LINER. Absorption
  - NGC7130. Sy2. Emission
HF 1-0 Absorption

- UGC05101

\[ N_{HF} \sim 1.1 \times 10^{14} \text{ cm}^{-2} \]

For a source size of 10'' \[ \rightarrow \text{HF abundance} \sim 2.6 \times 10^{-8} \]

- Solar F abundance is \[ 3.5 \times 10^{-8} \text{ (Lodders 2003)} \]
HF 1-0 Absorption

- UGC05101

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\[ N_{HF} \] is a lower limit
  - Only HF in J = 0
  - Only clouds illuminated by the sub-mm continuum source
  - All the continuum measured is actually illuminating these clouds

\[ N_{H2} \] is a depends on the CO-to-H2 conversion factor and on the source size
HF 1-0 Emission in NGC7130

- Assuming optically thin emission \( N_{J=1} \sim 10^{11} \text{ cm}^{-2} \)

For solar abundance and excitation due to collisions with H2

\[ \downarrow \]

\[ \gg 20\% \text{ of the total molecular gas } n_{\text{H}_2} > 10^{10} \text{ cm}^{-3} \]

Again this is a lower limit!
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- IR Pumping. HF has a vibrational absorption band at 2.5 μm
  To be efficient radiation field $T > 730\, K \rightarrow 10^6$ times PDR of O star
  Only the AGN could produce such radiation field

- Chemical Pumping

- Collisions with electrons
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HF 1-0 Emission in NGC7130

- **IR Pumping.** HF has a vibrational absorption band at 2.5 μm
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Only the **AGN** could produce such radiation field

- **Chemical Pumping.** HF formed in a excited state
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  XDR around the **AGN**?
Mid-J CO Emission
CO Emission

- CO is mainly excited by collisions with \( \text{H}_2 \)

- We use RADEX: non-LTE code to predict the CO line intensities: Kinetic temperature, density and column density

- The observed CO SLEDs agree with kinetic temperatures \(~300-800\, \text{K}\) and densities \(~10^3-10^4\, \text{cm}^{-3}\)

- Warm molecular mass \(10^6-10^8\, \text{M}_{\odot}\)
Cold Molecular Gas

- Excess CO J=1-0 with respect to the model prediction (10-25%)

- Cold molecular gas produces lower-J CO lines (lower excitation temperature)

\[
\text{CO J} = 1-0 \text{ flux } \propto \text{H}_2 \text{ mass}
\]

\[
\text{CO-to-H}_2 \text{ conversion factor }
\]

\[
N(\text{H}_2) = 0.5 \times 10^{20} \ I(\text{CO J} = 1-0)
\]

\[\text{Downes & Solomon 2008}\]

Cold molecular mass \(10^{7.5} - 10^{9.6} \text{ Msun}\)
Cold and Warm Molecular Gas

- CO SLED. 2 components
  - Luminosity dominated by the warm component (mid-J CO lines)
  - Mass dominated by the cold component (low-J CO lines)

<table>
<thead>
<tr>
<th></th>
<th>Cold</th>
<th>Warm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>10%</td>
<td>90%</td>
</tr>
<tr>
<td>Mass</td>
<td>95%</td>
<td>5%</td>
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</table>

Warm gas
PDR or XDR?
PDR and XDR Models

- **PDR** fits CO $J<9$. Underpredicts CO $J\geq 9$

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PDR and XDR Models

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PDR and XDR Models

- **PDR** fits CO J<9. Underpredicts CO J>= 9
- **XDR models**, in general, fit better higher-J CO lines
  - **XDR A** High density
  - **XDR B** Intermediate density
    
    Models: L(CO)/L(X) \sim 10^{-4}
    
    Obs: L(CO)/L(X) \sim 10^{-2}

- **XDR C** Diffuse gas. Low surface brightness (> 100x lower than observed)
Comparing CO SLEDs

- Mrk 231. Sy1 LIRG. **XDR** (van der Werf+2010)

- NGC6240. Sy2 LIRG. **Shocks** (Meijerink+2013)

- Arp220. ULIRG. No **PDR**, no **XDR**, **shocks**? (Rangwala+2011)

- M82. Starburst **PDR+shocks** (Kamenetzky+2012)
AGN or Star-Formation?

Likely Star-formation in these galaxies

\[ \frac{L_{\text{CO}}}{L_{\text{IR}}} \approx 10^{-4} \]

\[ L_{\text{CO}} \sim 10^{-4} L_{\text{IR}} \]

\[ L_{\text{CO}} \sim 10^{-4} L_{\text{IR}} \]

Pereira-Santaella+2013

AGN luminosity

SFR

L~2 dex

L_{\text{[OIV]}} \sim L_{\text{sun}} \]

L_{\text{IR}} \sim L_{\text{sun}} \]

L_{\text{CO}} \sim L_{\text{IR}} \]

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Summary

- SPIRE/FTS view of warm molecular gas in galaxies
  - HF 1-0 as an AGN tracer
  - PDR? XDR? Shocks? We need more data (higher angular resolution, higher-J CO lines)
  - mid-J CO emission more likely related to SF in these galaxies