The 25 Meter Telescope and Studies of Nearby Galaxies

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Spectral Lines Available at High Site

<table>
<thead>
<tr>
<th>Species</th>
<th>Transition</th>
<th>E.P.¹</th>
<th>λ (µm)</th>
<th>A (s⁻¹)</th>
<th>n_{crit} (cm⁻³)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>N⁺</td>
<td>^3P₁ → ^3P₀</td>
<td>70</td>
<td>205.178</td>
<td>2.1 × 10⁻⁴</td>
<td>4.8 × 10¹</td>
</tr>
<tr>
<td>C⁰</td>
<td>^3P₂ → ^3P₁</td>
<td>63</td>
<td>370.415</td>
<td>2.7 × 10⁻⁷</td>
<td>1.2 × 10³</td>
</tr>
<tr>
<td></td>
<td>^3P₁ → ^3P₀</td>
<td>24</td>
<td>609.135</td>
<td>7.9 × 10⁻⁸</td>
<td>4.7 × 10²</td>
</tr>
<tr>
<td>^12CO</td>
<td>J = 13 → 12</td>
<td>503</td>
<td>200.273</td>
<td>2.4 × 10⁻⁴</td>
<td>5.6 × 10⁶</td>
</tr>
<tr>
<td></td>
<td>J = 11 → 10</td>
<td>430</td>
<td>236.614</td>
<td>1.6 × 10⁻⁴</td>
<td>3.7 × 10⁶</td>
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<tr>
<td></td>
<td>J = 7 → 6</td>
<td>155</td>
<td>371.651</td>
<td>3.6 × 10⁻⁵</td>
<td>3.9 × 10⁵</td>
</tr>
<tr>
<td></td>
<td>J = 6 → 5</td>
<td>116</td>
<td>433.338</td>
<td>2.2 × 10⁻⁵</td>
<td>2.6 × 10⁵</td>
</tr>
<tr>
<td></td>
<td>J = 6 → 5</td>
<td>111</td>
<td>453.497</td>
<td>2.0 × 10⁻⁵</td>
<td>2.3 × 10⁵</td>
</tr>
<tr>
<td>^13CO</td>
<td>J = 6 → 5</td>
<td>116</td>
<td>433.338</td>
<td>2.2 × 10⁻⁵</td>
<td>2.6 × 10⁵</td>
</tr>
</tbody>
</table>

¹Excitation potential, energy (K) of upper level above ground.
²CO: Collision partner H₂ (100 K). [Cl]: H & H₂, [NII]: e⁻.

Critical Densities, Energy above ground ensure:

- Important astrophysical probes of ionized gas, molecular clouds, photodissociation regions, shocked regions, and astro-chemistry
- Important cooling lines for much of the ISM
COBE FIRAS Spectrum of the Galaxy

- [CII] line is strongest cooling line from Galaxy ($L \sim 6 \times 7 \ L_\odot$)
  - Cools molecular cloud surfaces, atomic clouds, and HII regions
- [NII] lines $\sim 1/6$ and $1/10$ as bright as [CII]
  - Important coolants for low density ionized gas
  - Line ratio yields ionized gas density.
  - [NII] $^3P_1-^3P_0$ (205 $\mu$m) line has same density dependence as [CII] for ionized gas $\Rightarrow$ constrains fraction of [CII] from ionized medium
COBE FIRAS Spectrum of the Galaxy

- CO rotational transitions up to J = 8-7 detected
  - Strength of mid-J lines indicates substantial amounts of warm (T > 40 K), dense gas
  - Gas is particularly high excitation in the inner regions of the Galaxy
- [CI] lines are ubiquitous
  - Cooling in lines together amounts to total cooling in all of the CO lines
  - Line ratio is near unity, temperature sensitive
    \[ T_{\text{gas}} \approx 40 \text{ K} \]
The [CI] and CO(7-6) Lines

- [CI] line ratio gives $T_{\text{gas}}$
- Run of CO line intensity with $J$ constrains molecular gas pressure
- The CO(7-6) and [CI] $^3P_2$-$^3P_1$ (370 $\mu$m) lines are only 1000 km s$^{-1}$ (2.7 GHz) apart
  - easily contained in one extragalactic spectrum $\Rightarrow$
    - Excellent relative calibration
    - “Perfect” spatial registration

*This line ratio of particular interest, as it is very density sensitive*
The Extragalactic Niche

- **Low surface brightness in the short submm (200, 230, 350, and 450 um) windows:**
  It can be shown that the Atacama 25 m telescope is competitive per beam with any other terrestrial telescope existing or planned at these wavelengths.
  
  *This is especially true for continuum work* --

- **Extragalactic work requires modest resolving powers:**
  
  \[ R = \frac{\lambda}{\Delta \lambda} \sim 1000 \text{ to } 10,000, \text{ or } \Delta v \sim 300 \text{ to } 30 \text{ km s}^{-1} \]

  This can be achieved with direct detection spectrometers ⇒ significant sensitivity advantages possible.

- **Nearby galaxies are extended ⇒ multiple beam systems are desirable**

  At present, large format spectrometers are easier to implement with direct detection systems.
Continuum Observations of Galaxies

- The far-IR continuum emission from galaxies traces the deposition of optical starlight from nearby OB stars, or the diffuse ISRF – traces regions of star formation in an extinction free manner.

- Dust that peaks at 200 um is quite cold $T \sim 20$ K – trace the luminosity and mass of cold dust

- For warmer dust, the submm colors are insensitive to $T$, since we are typically in the Rayleigh-Jeans tail.

- However the warmer dust properties are constrained by examining the apparent emissivity law.
  - Temperature and emissivity law yield dust column (mass)
  - Combined with shorter wavelength observations, we get the far-IR luminosity of the galaxy e.g. 38 or 60 um SOFIA observations, for which $\theta_{\text{beam}} = 3.8''$ and 6'' respectively.
Continuum Observations

- The far-IR and visible morphologies of galaxies may often be quite different.
- IRAS and ISO imaging of the (optically) Sb galaxy M31 reveal a ring of cool dust – no spiral pattern is visible.
- There is also warm dust (star formation) in the nucleus.

M31: Haas et al. 1998
Continuum Observations of M31

- Most of the dust has a temperature of only 16 K – much cooler than inferred from IRAS data.
- The warm dust/cool dust ratio varies little across the galaxy ⇒ evidence for distinct dust populations.
- Cold dust mass ~ $3 \times 10^7 \, M_\odot$ ten times greater than that inferred from IRAS data alone!
- New dust mass, even if distributed uniformly would make the disk of M31 moderately opaque in the visible ($A_V \sim 0.5$).
Far-IR Continuum: Revealing the Starburst

For IR luminous galaxies, the submm continuum (esp. together with far-IR continuum) traces the far-IR luminosity in an extinction free manner so it reveals the locations and luminosity of the starburst.

For example, in the Arp 299 interacting system, components “B” (NCG 3690 nucleus) and “C” (overlap) appear equally important with “A” (IC 694 nucleus) at even mid-IR wavelengths.

However, at 38 um the continuum traces reveals that most (~75%) of the emission arises in the nucleus of IC 694!
Submm Line Observations: The [CI] and mid-J CO Lines

- The CO(6-5) line first reported from a few starburst nuclei in 1991 (Harris et al. 1991)
  - Run of CO line intensity with J constrains molecular gas conditions
  - Gas is both warm, and dense – modeling was fit into a PDR (stellar UV heating) scenario

- Since then, several galaxies have been detected, and many mapped in the lower J [CI] (610 um) line:
  - The [CI] line intensity traces C⁰ column (high T, high n limit)
  - The [CI] line is an excellent tracer of molecular clouds in galaxies, perhaps better than CO (Gerin and Phillips, 1999)
  - The combined cooling in the [CI] lines is comparable to the CO line cooling – most (85%) of this is in the 370 um line.
  - There is a very high C⁰/CO abundance ratio (~ 0.5) in these galaxies – much higher than Milky Way values. This is either due to:
    - Fractionally more photodissociated gas due to cloud fragmentation
    - More C⁰ produced molecular cloud interiors due to chemical processes associated with high cosmic ray fluxes or non-equilibrium chemistry
Mid-J CO Observations of Galaxies

Recently, Bradford et al (2002) mapped the starburst nucleus of NGC 253 in the CO(7-6) line. They find that the run of $^{12}$CO and $^{13}$CO lines can be modeled as a single component!

- Warm molecular gas mass ~ 10 - 30 times the PDR gas mass as traced in its [OI] and [CII] line emission
- PDR scenarios fail to account for heating of this much molecular gas
- The most likely source of the heating is the strong (800 x MW value) cosmic ray flux from the starburst
- Also provides a natural mechanism for heating the entire volume of the gas.

Integrated $^{12}$CO and $^{13}$CO line intensities from the nucleus of NGC 253 together with our adopted model of the excitation (Bradford et al. 2002)
Recently we have detected and mapped the [CI] and CO(7-6) lines simultaneously from NGC 253:

- The line ratio is density sensitive: strength of CO(7-6) ⇒ very dense ISM
- The [CI] (370 um)/(610 um) line ratio (~ 1.9) is sensitive to gas temperature, and yields $T_{\text{gas}} > 100$ K as for the CO gas
- From distribution and physical conditions, $C^o$ and CO well mixed ⇒ Cosmic ray enhancement of $C^o$ abundance

SPIFI-JCMT [CI] 371 um & CO(7→6) (372 um) spectrum of the NGC 253 nucleus.
CO(7-6) and [CI] from NGC 4038/4039

- [CI] Line intensity essentially constant
- CO(7 → 6) greatly enhanced at the starburst interaction zone reflecting the high gas excitation there
- Strong mid-J CO emission reflects influence of OB stars
Bars, Spiral Arms, and Starformation: M83

ISO: [OIII] 88 µm
ISO: [NII] 122 µm
ISO: [CII] 158 µm

Nearby galaxies are easily imaged in the [NII], [CII] and mid-J CO lines

- Spiral arms/inter-arm contrast highest for [OIII] 88 µm line ⇒ earliest type stars (star formation) reside in the spiral arms
- At bar/spiral arm interfaces, [OI], [CII], & [OIII] strongly enhanced ⇒ greatly enhanced starformation activity similar to Orion interface region 0.2 pc from Θ¹C! Expect strong mid-J CO line emission there.
- The SW bar region strong in Hα and CO as well (e.g. Kenney & Lord, 1991) ⇒ Orbit crowding likely triggers a massive burst of starformation
Bars, Spiral Arms, and Starformation: M83

Can easily resolve spiral arms:
Tracing far-IR continuum, ionized gas ([NII]), atomic/molecular gas [Cl] and dense molecular gas (mid-J CO) as the interstellar medium is compressed and recycled in spiral density waves and bar structures.
Edge on Galaxies: NGC 891

2” beam ⇔ 100 pc

Easy to image nearby edge-on galaxies in the lines and continuum tracers

- Scale height of ISM – energetics -- super bubbles, chimneys
  - [NII] as extinction free, low excitation probe of ionized gas
  - [CI] traces atomic and/or molecular ISM
  - Regions of high mass star formation should appear in the mid-J CO lines
- Far-IR continuum, star formation and cold dust
- At 10 Mpc, 2” ⇔ 100 pc
- Scoville et al find CO(1-0) scale height ~ 200-300 pc
Seyferts Galaxies: Detecting the Torus?

Dominant paradigm is that the jets often seen emanating from the nuclei of active galaxies are confined by a pc scale dense molecular torus

- Krolik and Lepp (1989) predicted that this torus would be very warm (1000 K) and dense ($\sim 10^7$ cm$^{-3}$):
  - CO molecule pumped up to very high rotational levels
  - Low and mid-J line emission may be difficult to detect due to intervening molecular ISM heated by starburst – in warm, optically thick cloud, the luminosity is proportional to $J^3$.
- Key to detection is spatial resolution – to pull the CO emission out of the foreground gas
- Also need very high sensitivity in the far-IR rotational lines
- 25 m Atacama telescope might just be the tool – $J = 13 – 12$ and $J = 11-10$ lines come through in 200 and 230 um windows.
- Beam size at 20 Mpc $\sim 200$ pc – still quite some beam dilution!
25 m beam at 200 µm

Line flux prediction ~ $5 \times 10^5 \, L_\odot$, or $7 \times 10^{-17} \, W/m^2$! – easily detectable SNR 500!
Conclusions

- A powerful Atacama 25 m niche is low resolution spectroscopy of extended extragalactic sources.
- The submm continuum is used to trace dust properties and mass, and (together with far-IR continuum) deposition of energy.
- Submm lines trace physical properties of ionized, atomic and molecular gas in an extinction free manner.
  - Easily excited for typical ISM parameters
    -⇒ Are important, if not dominant coolants
- Will study star formation in ULIGs, interacting galaxies, normal spirals, etc, and possibly detect confining torus for Seyfert galaxies.