GREAT observations reveal strong self-absorption in [CII] 158 µm emission from NGC 2024

Urs U. Graf
Collaborators and Acknowledgements

- The GREAT team
- SOFIA staff in Palmdale and beyond
Outline

- GREAT Introduction
- NGC 2024:
  - Introduction
  - $[^{12}\text{CII}]$ map
  - $[^{13}\text{CII}]$ map
  - Line profile analysis
  - [CII] Hyperfine line ratios
The GREAT team (part of it)

GREAT: a modular dual color heterodyne spectrometer

Basic Science observing period (2011): mostly L1 (~1400 GHz) and L2 (~1900 GHz)
GREAT in the Lab

SOFIA P1-rack
Monitor drawer
Power distributor
Ethernet-HUB
Obs-computer
IF-Power-supply
IF Pre-processor
IF LO-supply
IF-processor
Chopper control

Cryostats
Cold-load
SI mounting flange

Oscilloscope
LO-synthesizer #1
Optics control

Mixer-BIAS #1 & #2
Instrument computer
Power-supply
LO-synthesizer #2
1.9 THz Solid-state LO
1.4 THz Solid-state LO

FFTS
CTS #1 and #2
AOS-system

Picture taken by DLR
GREAT configuration during NGC 2024 observations (Nov 2012):

- L2 (1900 GHz)
- M (2500 GHz, experimental) – inoperable due to LO failure
Receiver Noise Temperature

\[ T_{RX} \sim 4000 \, \text{K} \]

@ 1.9 THz
First Detection of Interstellar [CII] was made in NGC 2024

DETECTION OF THE 157 MICRON (1910 GHz) [C II] EMISSION LINE FROM THE INTERSTELLAR GAS COMPLEXES NGC 2024 AND M42

RAY W. RUSSELL, GARY MEHLNICK, GEORGE E. GULL, AND MARTIN HARWIT
Center for Radiophysics and Space Research, Cornell University
Received 1980 April 7; accepted 1980 May 28

ABSTRACT

We present the first detection of the [C II] fine-structure emission line at a wavelength of 157 μm. The [C II] line strengths are $7.1 \times 10^{-18}$ and $1.0 \times 10^{-18}$ W cm$^{-2}$, respectively, in NGC 2024 and M42. The line-to-continuum ratio is higher in NGC 2024 where the continuum is $7.0 \times 10^{-18}$ W cm$^{-2}$ μm$^{-1}$, in contrast to M42 where it assumes a value of $2.6 \times 10^{-18}$ W cm$^{-2}$ μm$^{-1}$. The respective luminosities in the line are $\sim 50$ and $80 L_\odot$. The observations were obtained with a stressed Ge:Ga photoconductor.


I. INTRODUCTION

The fine-structure transition of singly ionized carbon, [C II], has long been considered to be one of the principal means for cool interstellar atomic clouds to radiate energy into space. At temperatures below 200 K [C II] emission has been predicted to dominate the cooling of gas clouds (Dalgarno and McCray 1972). Although this line has been discussed in theoretical studies for over a decade, practical difficulties (including a lack of sensitive high-resolution far-infrared spectrometers and an uncertainty in the actual line position) have prevented direct observation.

IV. CONCLUSION

We have obtained the first observations of the 157 μm [C II] cooling line. On the assumption that the 157 μm [C II] radiation emanates from the same region as 63 μm [O I] radiation, i.e., from neutral H I layers surrounding the H II domain, we can derive approximate gas temperatures. Optical depth effects in the 157 μm line may be significant but have not been taken into account in our calculations because our data base is still too restricted.
NGC 2024

Bright HII region shadowed by an optically opaque dust lane
NGC 2024 (zoomed)

- E-W Ionization front
- Radio absorption lines at 9 km/s
- Molecular lines N-S extended
- Optically thin CO lines have 2 peaks @ 9 km/s and 11 km/s
Standard source model: 2 emission components

- Cold foreground @9 km/s
- Warm background @11 km/s
[CII] integrated intensity map

- [CII] is very strong: > 600 K km/s
- Closely follows 8 µm continuum (i.e. UV heated dust)
2 main velocity components: 8-9 km/s and 11-12 km/s
Dip at 10 km/s
Slight spatial anticorrelation between the 2 velocity components
$^{18}\text{O}$ 2-1 vs. $[\text{C}\text{II}]$ near FIR5

Suggests 2 emission components in $[\text{C}\text{II}]$ too, but we also got $[^{13}\text{C}\text{II}]$...
CII fine structure lines at 1.9 THz

### Constants for CII Determined by LMR

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(^{12}\text{C}^+ P_{3/2} \leftarrow ^2 P_{1/2})$</td>
<td>1900.5369(13) GHz</td>
</tr>
<tr>
<td>$E(^{13}\text{C}^+ P_{3/2} \leftarrow ^2 P_{1/2})$</td>
<td>1900.5458(21) GHz</td>
</tr>
<tr>
<td>$g_J = 1/2$</td>
<td>0.66576(11)</td>
</tr>
<tr>
<td>$g_J = 3/2$</td>
<td>1.33412(11)</td>
</tr>
<tr>
<td>$\frac{1}{4}(A_{1/2} - 3A_{3/2})$</td>
<td>80.3(7) MHz</td>
</tr>
</tbody>
</table>

### Estimated Zero-Field Transition Frequencies for $^{13}$C II

<table>
<thead>
<tr>
<th>Transition</th>
<th>Frequency (GHz)</th>
<th>Relative Intensity</th>
<th>$\Delta(^{13}\text{CII}^{12}\text{CII})$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 $\leftarrow$ 1</td>
<td>1900.4661(23)$^a$</td>
<td>44.4%</td>
<td>-11.2</td>
</tr>
<tr>
<td>1 $\leftarrow$ 1</td>
<td>1900.136(10)$^b$</td>
<td>20.0</td>
<td>-63.2</td>
</tr>
<tr>
<td>1 $\leftarrow$ 0</td>
<td>1900.950(15)$^b$</td>
<td>35.6</td>
<td>65.2</td>
</tr>
</tbody>
</table>

Cooksy, Blake, Saykally 1986
Strong [\textsuperscript{12}C\textsc{ii}] & [\textsuperscript{13}C\textsc{ii}] emission

All three [\textsuperscript{13}C\textsc{ii}] HFS satellites detected

\textsuperscript{12}C\textsc{ii} & 8 \mu m (MSX)

\textsuperscript{13}C\textsc{ii} & [\textsuperscript{12}C\textsc{ii}]

\textsuperscript{12}C\textsc{ii}

NGC 2024
[\textsuperscript{13}\text{CII}] reveals self-absorption!

Data replotted on common v\textsubscript{LSR} scale

[\textsuperscript{12}\text{CII}] line divided by 10
Physical Properties

- $[^{13}\text{C}]$ emission requires column density of $N(^{13}\text{C}^+) \approx 2.6 \times 10^{17} \text{ cm}^{-2} \rightarrow N(\text{H}) \approx 1.6 \times 10^{23} \text{ cm}^{-2}$
  This is as high as the molecular column density!

- Temperature of background component not well constrained due to foreground absorption, but needs to be $>165$ K, probably several 100 K
  Optically thin limit: 800 K

- Temperature of absorbing foreground: $T_{\text{FG}} < 90$ K

- Column density of absorbing foreground: $N_{\text{FG}}(\text{C}^+) \ 10^{18} \text{ cm}^{-2} \rightarrow N_{\text{FG}}(\text{H}) \approx 10^{22} \text{ cm}^{-2}$
HII region / molecular cloud IF → Photon Dominated Region (PDR)

- $C^+$, C, CO layered within $\sim 1-2$ $A_v$ ($N_{H_2} = 10^{21}$ cm$^{-2}$)
- Many (10-100) IFs required for large column density of warm CO emission
  → Clumpy interface
  → $C^+$, C, and warm CO spatially coexistent
PDR Modelling

• One PDR surface cannot produce the strong emission that we observe
• Edge-on geometry (ionization front) may help locally
• Clumpiness could make the difference. Preliminary estimates show that a clumpy cloud model can reproduce the observed intensities
• Need more data for detailed modelling
Anomalous Hyperfine Ratio?

- 2-1/1-0 ratio should be 1.25
- measured ratio is \(~2\)
- D. Neufeld: Corrected HFS weights yield ratio of 2.5
Simultaneous Fit with Fixed Hyperfine Ratios

Original HF ratios

Recalculated HF ratios

Fit is believable now!
Conclusion

- [CII] is self-absorbed
- Kinematic signature differs from CO isotopes
- Column densities are very high:
  - $\geq 10^{23} \text{ cm}^{-2}$ @ several 100 K in background
  - $\geq 10^{22} \text{ cm}^{-2}$ @ $<100$ K in absorbing foreground
- Anomalous hyperfine intensity ratio probably explained by error in original paper

High spectral resolution is crucial!
Conclusion

- $[^{12}\text{CII}]$ is self-absorbed
- Kinematic signature differs from CO isotopes
- Column densities are very high: $\geq 10^{23}$ cm$^{-2}$ at several 100 K in background
- $\geq 10^{22}$ cm$^{-2}$ at $<100$ K in absorbing foreground
- Anomalous hyperfine intensity ratio probably explained by error in original paper
- High spectral resolution is crucial!
Thank You