[C II] and [N II] Observations of Ionized Gas at the Edge of the Central Molecular Zone*

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The Superlative Central Molecular Zone

\[ 12\text{CO Intensity} \]

\[ \text{[C II] Intensity}\]

\[ \text{BICE } \Delta V = 175 \text{ km/s} \]

\[ \text{FIR Continuum} \]

\[ \text{CO from Dame et al. (2001) & Nobayama CO survey Oka et al (1998); [C II] BICE survey Nakagawa et al. (1998)} \]
Outline

• Overview of CMZ
• [N II] and [C II]
• Electron abundance
• Results
• Ionization Sources
• Conclusion

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Central Molecular Zone (CMZ)

- CMZ ≈400 pc X 80 pc around the Galactic Center
- Giant Molecular Clouds (GMCs) ≈few×10^7 M☉
- GMCs: n(H₂) > 10 X disk
- T_{kin} ≈ 40 – 200K vs 10 - 35K
- ΔV ≈ 20 km/s vs 3-4 in disk
- H ≈ (2 – 10)×10^5 M☉

- H^+ ≈ (6–10)×10^5 M☉: WIM (H^+), HIM(H^+,He^+)
- Enhanced energy environment: HII regions, accreting black holes, X-rays, cosmic rays, supernova, turbulence.

Ionized Gas in the Galaxy

- Ionized gas is an important component of the ISM
- It occupies most of the volume
- Couples gas to magnetic fields
- Physical state of the ionized gas is a result of sources of ionization and heating (star formation rate, accreting black holes, cosmic rays, etc.)
- Boundary pressure for the HI clouds and GMCs
Distribution of CMZ Gas - Molecular

Fig. 2.—Maps of the $^{12}$CO $J = 1$–0 and $^{13}$CO $J = 1$–0 line emission integrated over the velocity range $V_{LSR} = -220$ to $+220$ km s$^{-1}$. Contours drawn at every 200 K km s$^{-1}$ for $^{12}$CO and at every 100 K km s$^{-1}$ for $^{13}$CO. Mapping areas are indicated by solid lines (four beams) and dashed lines (three beams). We have smoothed the data using a Gaussian weighting function with $60\alpha$ full width at half-maximum. The distributions of the two emission lines are basically similar, while $^{12}$CO emission is typically 5 times stronger than $^{13}$CO emission. The mean $^{12}$CO/$^{13}$CO luminosity ratio over the $^{13}$CO mapping area is 5.19.

Nobayama Telescope (Oka et al. 1998)
Measuring Electron Abundance (Examples)

- Radio-Wave dispersion against embedded (pulsar) or background (extragalactic) sources
- Radio continuum from thermal free-free emission
- Radio recombination lines, e.g. H110α.
- X-ray lines – Fe ions (Fe XXV) probes very hot gas
- Visual – e.g. Hα λ6563
  - Wisconsin H Alpha Mapper (WHAM)
- Far IR fine-structure lines, e.g. [C II], [N II], [O III]
  - [C II] at 1.90 THz (158 μm) and [N II] at 1.46 THz (205 μm)
  - Advantage of high spectral resolution with heterodyne receivers
Radio Continuum and Recombination

- Mezger & Pauls (1979) derived $n(e)$ distribution in CMZ using radio continuum (thermal free-free) and recombination lines
- Modeled WIM as two oblate spheroids
  - $(225 \text{ pc})^2 \times 90 \text{ pc}$ with $n(e) \approx 8 \text{ cm}^{-3}$ & $T(e) \approx 5000 \text{ K}$, $M(H^+) \approx 4.7 \times 10^5 \text{ M}_\odot$
  - $(95 \text{ pc})^2 \times 55 \text{ pc}$ with $n(e) \approx 18 \text{ cm}^{-3}$ & $T(e) \approx 5000 \text{ K}$, $M(H^+) \approx 1.2 \times 10^5 \text{ M}_\odot$
- Total inner $n(e) \approx 26 \text{ cm}^{-3}$ & $M(H^+) \approx 5.9 \times 10^5 \text{ M}_\odot$
- $n(e)$ is very high compared to $n(e) \approx 0.01$ for Disk WIM
n(e) from Radio Dispersion

Lazio & Cordes (1998) conclude dispersion is due to scattering off either:

a. Photoionized skins of molecular clouds with $T(e) \approx 10^4$ K and $n(e) > 10^3$ cm$^{-3}$, or
b. Interface between molecular clouds and the hot ambient gas with $T(e) \approx 10^{5-6}$ K and $n(e) \approx 5 - 50$ cm$^{-3}$

Roy (2013) observed 62 compact extragalactic sources towards CMZ

a. Scattering medium is patchy on scales of $\approx 10'$ (25 pc) with $n(e) \approx 10$ cm$^{-3}$

b. Ionized interfaces with dense GMCs are likely source of scattering.

see also review by Ferriere et al. (2007)
HIM: X-Ray Observations

Iron distribution

- X-ray thermal emission at 0.5 to 2 keV (ROSAT) is enhanced towards CMZ - Hot Ionized Medium (HIM)
- Hard X-ray emission from Fe XXV and Fe XXVI (Koyama et al. 1996): \( kT > \) several keV, \( n(e) \approx 0.03 \text{ cm}^{-3} \), \( M(H^+) \approx 10^5 \ M_\odot \)
n(e) from [N II] and [C II]

• Use [N II] and [C II] far-infrared lines to probe the electron density and ionization in the CMZ
• ADVANTAGE: High spectral resolution identifies components and probes physical properties
• [C II] traces all ionized regions as I.P. = 11.1 eV
• [N II] traces more highly ionized gas: I.P. = 14.53 eV
• Herschel HIFI OTF [C II] strip maps → morphology
• SOFIA GREAT [C II] and [N II] pointed observations along a strip across the edge of the CMZ → n(e)
Edge of the CMZ in CO and [C II]

12CO NANTEN map of Giant Magnetic Loops and CMZ (Fukui et al. 2006)

GOT C+ [C II] Survey
Langer et al. (2014)

Sgr E

Loop 1

r ≈ 670 pc

r ≈ 200 pc

359° 358° 357°
$^{12}$CO map from Oka et al. 1998

Herschel HIFI [C II] and Mopra $^{12}$CO

$^{12}$CO/5 (358.7°, 0°)

[C II] probes the ionized edge of these GMCs

$^{12}$CO/S
CMZ [C II] OTF Map

[C II] strongest at CO boundary – limb brightening

HIFI OTF
GREAT +

HIFI OTF [CII] intensity (color)
Contours CO -210 to -220 km/s (Oka 1998)
GREAT [C II] & [N II] along $b=0^\circ$

[C II] detected at all 6 LOS – 2 components

[N II] detected at 4 LOS where S/N was best – 2 components

Components

$V_{lsr}(\text{km/s})$  $\Delta V(\text{km/s})$

-207       $\approx$25-30
-174       $\approx$25-30
GREAT [CII] & [NII] – Data Reduction Issues

Atmospheric H$_2$O line in [C II] band
Emission in reference off position
CO and HI ($b=0^\circ$)

**ThrUUMS** (Three-mm Ultimate Mopra Milky Way Survey)

HI Survey (McClure-Griffiths et al. 2012)
Line Parameters

\textbf{Table 1. Integrated line intensities}

\begin{tabular}{lcccc}
\hline
Los & \text{(C Ii)}^{a,b} & \text{(N II)}^{c} & \text{I(CO)} & \text{I(H I)} \\
\hline
\text{V}_{lsr} = -207 \text{ km s}^{-1} & & & & \\
358.45+0.0 & 63.4 & 26.4 & 6.7 & 1047 \\
358.55+0.0 & 45.4 & 15.4 & 26.6 & 1904 \\
358.60+0.0 & 47.6 & 7.1 & 60.6 & 2189 \\
358.65+0.0 & 38.6 & - & 101.9 & 2539 \\
358.70+0.0 & 45.4 & 12.4 & 98.9 & 2923 \\
358.75+0.0 & 57.4 & - & 110.5 & 3235 \\
\text{V}_{lsr} = -174 \text{ km s}^{-1} & & & & \\
358.45+0.0 & 21.1 & 8.2 & - & 730 \\
358.55+0.0 & 12.2 & 8.8 & - & 1212 \\
358.60+0.0 & 43.0 & 3.7 & - & 1544 \\
358.65+0.0 & 25.5 & - & - & 1855 \\
358.70+0.0 & 15.3 & 5.3 & - & 2177 \\
358.75+0.0 & 21.8 & - & 9.8 & 2522 \\
\hline
\end{tabular}

\begin{itemize}
\item a) Integrated intensities are in units of K km s\(^{-1}\). We only report detections with a SNR \(\geq 3\), see text.
\item b) Typical rms noise in the [C Ii] integrated intensity is \(\sim 1.4\) K km s\(^{-1}\).
\item c) Typical rms noise in the [N II] integrated intensity is \(\sim 1.3\) K km s\(^{-1}\).
\end{itemize}

SNR ranges from 4 to 20 for I(N II) and 8 to 45 for I(C II)
\(\Delta V\) of order 25 to 35 km/s
n(e) from [N II] – 2 levels

Electron collisions dominate excitation.
Solve the population of the 3 levels assuming $\tau << 1$.

$n(e)$ sensitive to ratio of 122\(\mu\) to 205\(\mu\) line only for $n(e) > 10$ cm\(^{-3}\)
1-0 line difficult to detect for $n(e) < \text{few cm}^{-3}$ & 2-1 is even harder.

\[ [\text{N II}] \text{ Excitation} \]
\[ N(N^+) = 6 \times 10^{16} \text{ cm}^{-2} \]
\[ \Delta V = 25 \text{ km/s} \]

\[ \begin{align*}
\text{Energy/k (K)} & \quad 0 & \quad 50 & \quad 100 & \quad 150 & \quad 200 \\
\text{3}P_2 & \quad 2459 \text{ GHz} & \quad 121.9 \mu \text{m} & \\
\text{3}P_1 & \quad 1461 \text{ GHz} & \quad 205.2 \mu \text{m} & \quad 2.1 \times 10^{-9} \text{ s}^{-1} & \quad \Delta E/k = 70.2 \text{ K} \\
\text{3}P_0 &
\end{align*} \]
\( \tau << 1 \)

\[
I_{10}([N\text{II}]) = T_{10}(K) \Delta V
\]

\[
= \frac{hc^3}{8\pi V_{10}^2} A_{10} f_1(N^+) N(N^+) \text{ cm}^{-2}
\]

Where \( f_1 \) is the fractional population of \(^2\text{P}_1\) state of \(N^+\) and is a function of \(n(e)\)

With only one line need to estimate \(N(N^+)\)

Assume uniform conditions: \(N(N^+) = n(N^+)L \text{ cm}^{-2}\)

\[
I_{10}([N\text{II}]) \approx 5 \times 10^{-16} (n(N^+)L) f_1 \text{ cm}^{-2}
\]
$n(e)$ from $[N\,II] - 1$ transition (2/2)

$n(N^+) = x(N^+)n(H^+)$

$n(H^+) \approx n(e)$

$I_{10}([N\,II]) \approx 0.16x_-(N^+)L_{pc}n(e)f_1(N^+) \text{ cm}^{-2}$

$f_1(N^+)$ is independent of $N(N^+)$ if $\tau \ll 1$

$n(e) \ll n_{cr}(e): f_1 \propto n(e)$

$n(e) \approx \left[ \frac{6.4I([N\,II])n_{cr}(e)}{L_{pc}x_-(N^+)} \right]^{0.5}$

$n(e) \gg n_{cr}(e): f_1 \rightarrow \text{const}$

$n(e) \propto \left[ \frac{I([N\,II])}{L_{pc}x_-(N^+)} \right]^{\approx 1}$
Model Parameters

-207 km/s component
  - [C II] limb brightened
  - Ionized layer ≈ 15 pc thick
  - $X(N^+) \approx 1.6 \times 10^{-4}$ (3xSolar)
  - Solve $n(e)$ for each $I([NII])$
  - Not very sensitive to $x(N^+)$ & $L_{pc}$

-174 km/s component
  - OTF HIFI map of this weaker [C II] component is not good enough to reveal morphology of emission region
  - Assume same parameters as -207 km/s component
**Electron and Column Densities**

Table 2. Electron density and nitrogen column density

| LOS     | V_{lsr} a $|$ n(e) b | N(N$^+$) c | N(H$^+$) | n(e) d | N(N$^+$) e | N(H$^+$) |
|---------|----------------------|-------------|-----------|--------|------------|-----------|
| 358.45  | -207                 | 20.7        | 1.5e17    | 9.6e20 | 9.9        | 7.5e16    | 4.6e20    |
| 358.55  | -207                 | 14.6        | 1.1e17    | 6.8e20 | 10.4       | 7.9e16    | 4.8e20    |
| 358.60  | -174                 | 9.1         | 6.9e16    | 4.2e20 | 6.3        | 4.8e16    | 2.9e20    |
| 358.65  | -174                 | -           | -         | -      | -          | -         | -         |
| 358.70  | -174                 | 12.8        | 9.7e16    | 5.9e20 | 7.7        | 5.9e16    | 3.6e20    |
| 358.75  | -174                 | -           | -         | -      | -          | -         | -         |
| Average | -207                 | 14.3        | 1.1e17    | 6.6e20 | 8.6        | 6.5e16    | 4.0e20    |

a) In km s$^{-1}$. b) Densities in cm$^{-3}$. c) Column densities in cm$^{-2}$. d) In cm$^{-3}$. e) All LOS are along b = 0°.

**Table 3. C$^+$ column densities and intensities**

<table>
<thead>
<tr>
<th>LOS</th>
<th>N(C$^+$)</th>
<th>I_{H^+}([Cu])</th>
<th>I_{H^+}([C II])</th>
<th>N_{H^+}(C$^+$)</th>
<th>N_{H^+}(H$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-207</td>
<td>4.9e17</td>
<td>64.1</td>
<td>-0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-207</td>
<td>3.5e17</td>
<td>38.5</td>
<td>7.0</td>
<td>4.2e17</td>
<td>8.2e20</td>
</tr>
<tr>
<td>-207</td>
<td>2.2e17</td>
<td>18.3</td>
<td>29.3</td>
<td>1.8e18</td>
<td>3.5e21</td>
</tr>
<tr>
<td>-207</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-174</td>
<td>3.0e17</td>
<td>31.3</td>
<td>14.1</td>
<td>8.6e17</td>
<td>1.7e21</td>
</tr>
<tr>
<td>-174</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

| Average | -207 | 3.4e17 | 38.1 | 16.8 | 1.0e18 | 2.0e21 |
| Average | -174 | 2.0e17 | 16.9 | 11.5 | 7.0e17 | 1.4e21 |

a) All LOS are at b = 0°. b) Column density in cm$^{-2}$. c) Intensity of [Cu] in the [N II] emission region in K km s$^{-1}$. d) V_{lsr} in km s$^{-1}$. e) Negative intensities are not included. f) Assumes T$_{e}$=100K and n(H$_2$) = 300 cm$^{-3}$.

- **V_{lsr} = -207 km/s component**
  - $n(e) = 9 - 21$ cm$^{-3}$
  - $N(N^+) = (7 - 15) \times 10^{16}$ cm$^{-2}$

- **V_{lsr} = -174 km/s component**
  - $n(e) = 6 - 10$ cm$^{-3}$
  - $N(N^+) = (5 - 8) \times 10^{16}$ cm$^{-2}$
Results

• [N II] and [C II] Detections provide evidence of hot highly ionized gas with n(e) ≈ 5 to 25 cm\(^{-3}\) in a thick layer surrounding GMCs in the Sgr E region.

• n(e) consistent with suggestions by Lazio & Cordes (1998) and Roy (2013) that dispersion of radio waves in the CMZ is primarily by scattering at the interface of clouds with a dense hot ionized medium.
Ionization Sources (1/3)

- Electron collisional ionization
- Cosmic ray ionization
- EUV photoionization
- X-ray photoionization
- Proton charge exchange
  - UV + H $\rightarrow$ H$^+$ + e
  - H$^+$ + N $\leftrightarrow$ H + N$^+$ ($\Delta E = 0.94$ eV $\approx 11,000$ K)
Ionization Sources (2/3)

- Electron collisional ionization requires very high kinetic temperatures as I.P. = 14.53 eV

- Cosmic ray ionization needs $10^{-12} \text{s}^{-1}$
  - Observations of $\text{H}_3^+$ in CMZ (Goto et al. 2014) suggest rate is too low by orders of magnitude
Ionization Sources (3/3)

- EUV photoionization: Need EUV flux $6 \times 10^6$ photons/cm$^2$/s – source massive star formation (O & B)
- X-ray photoionization of nitrogen & carbon about $10^3$ larger than corresponding H photoionization
  - Sources: diffuse X-rays, stellar sources, accreting black holes (stellar and massive)
- Charge exchange: $H^+ + N \leftrightarrow H + N^+ (\Delta E = 0.94$ eV)
  - H ionized by UV
  - $T_{\text{kin}} \approx 6,000$ K to 15,000 K depending on theoretical cross sections (see Lin et al. 2005; Langer et al. 2015)
  - Heating source: Shocks? Turbulent dissipation? EUV & X-rays?
Compact and Diffuse HII Sources

- Sgr E is an active star-forming HII region associated with a GMC
- VLA radio continuum map of Sgr E region (Liszt 1992)
  - 18 compact HII sources
    - $n(e) \approx \text{few} \times 10^2 \text{ cm}^{-3}$
    - ionizing stars are likely B0 or brighter
  - diffuse emission $l = 358.8^\circ$ to $358.95^\circ$
Edge of CMZ in IR

24 µm sources associated with the CO cloud, and the edge of the [C II] limb brightened arc

Spitzer 24 µm (blue)
Herschel 70 µm (green)
Herschel 500 µm (red)
from Molinari et al. (2014)
Hot Gas in the CMZ Traced by X-rays

Iron distribution

Suzaku image

Fe I (neutral)

Fe XXV (He-like)

Fe XXVI (H-like)

$T_{\text{kin}} \approx 5 - 7 \text{ keV}$

$\approx 50 \text{ pc}$

Suzaku X-ray satellite
(Koyama et al. 2007; from Matsumoto presentation)

Diffuse and discrete (> 9000)
X-Ray sources detected by Chandra (Wang et al. 2002; Muno et al. 2009)
Red: 1 – 3 keV
Green: 3 – 5 keV
Blue: 5 – 8 keV
Summary

- Spectrally resolved [C II] and [N II] far-IR lines provide detailed information about the location, morphology, and physical environment of the dense ionized gas in the CMZ.
- We find $n(e) \approx 5 - 25 \text{ cm}^{-3}$ at the interface of GMCs in regions about 10 – 20 pc in size.
- Mapping the ionized gas throughout the CMZ in spectrally resolved [N II] is difficult because of the weakness of the emission lines.
- GREAT on SOFIA provides a platform to study the electron abundance and ionization in select regions of the CMZ.
- To trace the highly ionized gas throughout the CMZ it will be important to extend the [N II] observations using a survey instrument on balloon borne or orbital platforms.