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FAR-INFRARED [C II] EMISSION FROM THE CENTRAL REGIONS OF SPIRAL GALAXIES

Kenji Mochizuki
Korea Astronomy Observatory, 61-1 Whaam-dong, Yusong-gu, Daejeon 305-348, Korea
E-mail: mochi@kao.re.kr
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ABSTRACT

Anomalies in the far-infrared [C II] 158 μm line emission observed in the central one-kiloparsec regions of spiral galaxies are reviewed. Low far-infrared intensity ratios of the [C II] line to the continuum were observed in the center of the Milky Way, because the heating ratio of the gas to the dust is reduced by the soft interstellar radiation field due to late-type stars in the Galactic bulge. In contrast, such low line-to-continuum ratios were not obtained in the center of the nearby spiral M31, in spite of its bright bulge. A comparison with numerical simulations showed that a typical column density of the neutral interstellar medium between illuminating sources at $h\nu \sim 1$ eV is $N_{\rm H} \lesssim 10^{21}$ cm^{-2} in the region; the medium is translucent for photons sufficiently energetic to heat the grains but not sufficiently energetic to heat the gas. This interpretation is consistent with the combination of the extremely high [C II]/CO J = 1–0 line intensity ratios and the low recent star-forming activity in the region; the neutral interstellar medium is not sufficiently opaque to protect the species even against the moderately intense incident UV radiation. The above results were unexpected from classical views of the [C II] emission, which was generally considered to trace intense interstellar UV radiation enhanced by active star formation.

Key words : galaxies: individual (Milky Way, M31)—galaxies: ISM—galaxies: spiral—infrared: ISM—ISM: lines and bands

I. INTRODUCTION

(a) Galactic [C II] Emission

The far-infrared (FIR) [C II] emission at $\lambda = 158$ μm is radiated from the $^2P_{3/2} \rightarrow {}^2P_{1/2}$ fine-structure transition of interstellar C^+ ions. This emission is one of the brightest lines observed toward spiral galaxies for the following reasons: carbon is an abundant element; the first ionization potential of carbon (11.3 eV) is lower than that of hydrogen; the excitation energy of the transition is only moderately high (91 K); the critical density of the transition is also only moderately high ($n \sim 10^3$ cm^{-3} for collision with hydrogen atom).

Figure 1 is a schematic view of a neutral cloud illuminated by stellar light. While most of the interstellar gas-phase carbon is incorporated in CO molecules in deeper regions of the cloud, the incident UV radiation converts CO molecules to C^+ ions near the surface (van Dishoeck & Black 1988). The incident stellar light also heats the gas the dust. The energy entered to the gas is radiated from the cloud in the form of the [C II] line emission as well as other infrared to millimeter lines. Thus, the [C II] emission traces recent star-formation activity, at least to some extent, as the FIR continuum emitted from the dust. In fact, the line intensity ratio of the [C II] to the CO J = 1–0 emission of normal galaxies increases with Hα equivalent width (Pierini et al. 1999).

However, there are some exceptions in which the [C II] emission does not trace the recent star-forming activity. On a galactic scale, following anomalies have been found so far:

1. Irregular galaxies yield extremely high [C II]/CO line ratios (Mochizuki et al. 1994; Lord et al. 1995; Poglitsch et al. 1995; Israel et al. 1996; Madden et al. 1997; Hunter et al. 2001; Israel et al. 2003).
2. The central one-kiloparsec regions of spiral galaxies show low FIR [C II]/continuum ratios in the case of the Milky Way (Nakagawa et al. 1995) and extremely high [C II]/CO line ratios in that of M31 (Mochizuki 2004).
3. Galaxies with high color temperatures of the dust emission tend to have low FIR ratios of the [C II] line to the continuum (Malhotra et al. 1997; Luhman et al. 1998; Malhotra et al. 2001).

The above topic 2 is reviewed in the present paper.

(b) FIR [C II]/Continuum Ratio

The [C II] emission along the Galactic plane was widely observed ($-10° < l < 25°$, $|b| \leq 3°$; Nakagawa et al. 1998) with the Balloon-borne Infrared Carbon Explorer (BICE). These observations showed nearly constant intensity ratios of $I_{[\rm C\,II]}/I_{40-120\,\mu\rm m} \simeq 6\times10^{-3}$, where $I_{[\rm C\,II]}$ is the frequency-integrated [C II] intensity and $I_{40-120\,\mu\rm m}$ is the continuum intensity integrated at 40 μm $\leq \lambda \leq$ 120 μm derived from Infrared Astronomical Satellite (*IRAS*) data.

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When the ISM in a steady state is considered, the FIR [C II]-to-continuum ratio can be written as:

$$\frac{I_{[\mathrm{C\,II}]}}{I_{\mathrm{FIR}}} = \eta_{[\mathrm{C\,II}]}\frac{\Gamma_{\mathrm{gas}}}{\Gamma_{\mathrm{dust}}}, \qquad (1)$$

where I_{FIR} is the frequency-integrated intensity of the FIR continuum, $\eta_{[\mathrm{C\,II}]}$ is the fraction of the [C II] contribution in the total gas cooling, and Γ_{gas} and Γ_{dust} are the heating rates of the gas and dust, respectively. The gas heating is generally dominated by energetic photoelectrons from grain surfaces illuminated by stellar light (de Jong 1977) in the neutral ISM. In this case, the heating ratio of $\Gamma_{\mathrm{gas}}/\Gamma_{\mathrm{dust}}$ can be replaced by the photoelectric-heating efficiency ϵ_{ph}, which is defined as the ratio of the energy carried away by the emitted photoelectrons to that absorbed by the grains, as follows:

$$\frac{I_{[\mathrm{C\,II}]}}{I_{\mathrm{FIR}}} = \eta_{[\mathrm{C\,II}]}\epsilon_{\mathrm{ph}}. \qquad (2)$$

The nearly constant $I_{[\mathrm{C\,II}]}/I_{\mathrm{FIR}}$ observed in the Galactic disk (Nakagawa et al. 1998) indicates that ϵ_{ph} is nearly constant and that the [C II] emission dominates the gas cooling ($\eta_{[\mathrm{C\,II}]} \simeq 1$), in wide ranges of physical conditions in the neutral ISM.

II. CENTER OF THE MILKY WAY

In contrast to the stable $I_{[\mathrm{C\,II}]}/I_{40-120\,\mu\mathrm{m}} \simeq 6\times10^{-3}$ in the Galactic disk, Nakagawa et al. (1995) obtained lower intensity ratios of $I_{[\mathrm{C\,II}]}/I_{40-120\,\mu\mathrm{m}} \simeq 2\times10^{-3}$ toward the central one-kiloparsec region of the Galaxy.

Lower ratios are also found in the Galactic disk, restricted to the vicinities of active star-forming sites (Stacey et al. 1991; Nakagawa et al. 1998). These ratios can be ascribed to the following two mechanisms (Hollenbach, Takahashi, & Tielens 1991):

1. Dust grains are positively charged when the incident UV radiation is intense. In this case, further emission of a photoelectron requires more energy because of the opposite charges of the grain and electron (de Jong 1977). This decreases ϵ_{ph} in equation (2) and consequently decreases the $I_{[\mathrm{C\,II}]}/I_{\mathrm{FIR}}$ ratio.

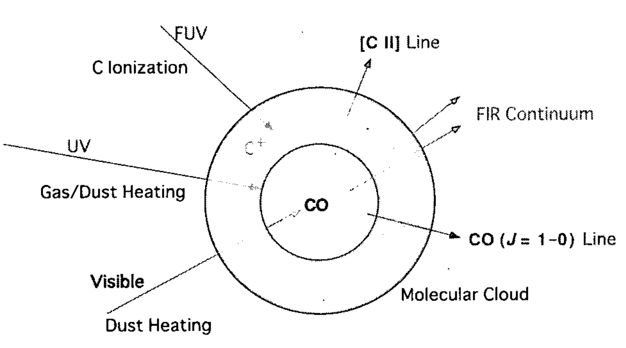

Fig. 1.— Schematic view of a neutral cloud illuminated by stellar light.

2. The [O I] 63 μm line can dominate the cooling of the neutral gas at a high temperature and a high density, because this line has a higher excitation energy and critical density than the [C II] line. This dominance decreases $\eta_{[\mathrm{C\,II}]}$, to result in a lower $I_{[\mathrm{C\,II}]}/I_{\mathrm{FIR}}$ ratio.

These mechanisms require intense stellar radiation, which is likely to be restricted to active star forming regions. Thus, low $I_{[\mathrm{C\,II}]}/I_{\mathrm{FIR}}$ ratios are observed at the regions having high color temperatures of the FIR dust emission in the Galactic disk (Nakagawa et al. 1995). The former mechanism also accounts for the low FIR [C II]/continuum flux ratios observed at galaxies with high 60 μm/100 μm flux ratios (Malhotra et al. 2001).

However, Nakagawa et al. (1995) showed that the situation is different for the Galactic center region; the $I_{[\mathrm{C\,II}]}/I_{40-120\,\mu\mathrm{m}}$ ratios in the region are systematically lower than those in the Galactic disk, irrespective of the 60 μm/100 μm intensity ratio. They ascribed the low $I_{[\mathrm{C\,II}]}/I_{40-120\,\mu\mathrm{m}}$ ratios to the softer interstellar radiation field in the Galactic center. The central kiloparsec region of our Galaxy is rich in photons sufficiently energetic to heat the dust grains but not sufficiently energetic to heat the gas, owing to many late-type stars in the Galactic bulge. This leads to a smaller ϵ_{ph} for the total wavelength range of the incident stellar light, and thus to a lower $I_{[\mathrm{C\,II}]}/I_{\mathrm{FIR}}$ ratio (Nakagawa et al. 1995; Malhotra et al. 2000; Pierini et al. 2003).

III. CENTER OF M31

(a) FIR [C II]/Continuum Ratio

For comparison with the [C II] emission in the Galactic center, Mochizuki (2000) observed that in the inner regions of M31 with the Long-Wavelength Spectrometer (LWS; Clegg et al. 1996) on board the Infrared Space Observatory (ISO; Kessler et al. 1996). This nearby spiral has a bright bulge (e.g., Martinez Roger, Phillips, & Sanchez Magro 1986) containing many late-type stars, which may reduce the FIR line-to-continuum ratio as observed in the Galactic center.

The [C II] emission was detected in the inner 1.6 kpc along the major axis of the galaxy. The obtained FIR line-to-continuum ratio in the M31 center was $I_{[\mathrm{C\,II}]}/\nu I_\nu(100\ \mu\mathrm{m}) \simeq 6\times10^{-3}$, 2–3 times higher than that in the Galactic counterpart and close to that in the general Galactic plane (Figure 2); the $I_{[\mathrm{C\,II}]}/\nu I_\nu(100\ \mu\mathrm{m})$ ratio in the M31 center is not reduced by the soft interstellar radiation, in spite of its bright bulge.

These observations were compared (Mochizuki 2000) to Photon-Dominated Region (PDR) models, in which equations of thermal balance and chemical equilibrium are solved at each depth into a neutral cloud illuminated by stellar light. The employed models are based on those of Mochizuki & Nakagawa (2000), which involve effects of variation in the size of the model cloud and the color of the incident radiation.

As Nakagawa et al. (1995) expected, the lower $I_{[\mathrm{C\,II}]}/\nu I_\nu(100\ \mu\mathrm{m})$ ratios observed in the Galactic cen-

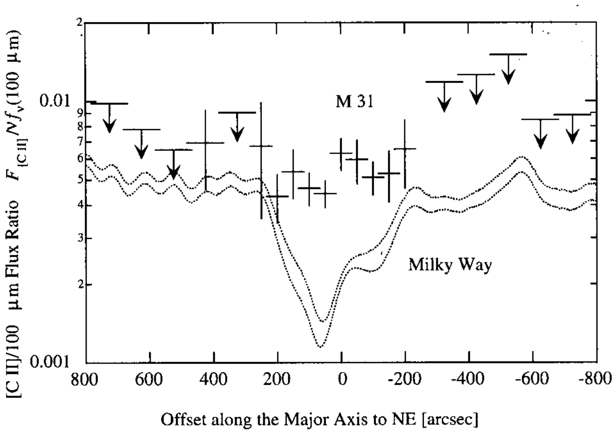

Fig. 2.— Distribution of the FIR [C II]/100 μm line-to-continuum ratio along the major axis of M31 (crosses; bars with arrows for upper limits), plotted as a function of the spatial offset (positive in the northeast) relative to the nucleus along the major axis of the galaxy (from Mochizuki [2000]). The horizontal bars indicate the size (FWHM) of the spatial sampling profile. The dotted curves simulate our Galaxy (Nakagawa et al. 1998), located at the distance of M31 and observed with the LWS beam.

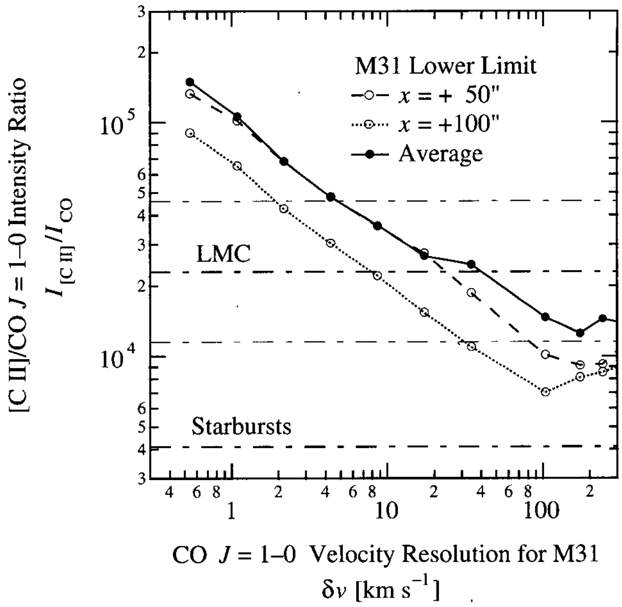

Fig. 3.— Lower limit (3.3σ) for the [C II]/CO J = 1–0 intensity ratio, $I_{[\mathrm{C\,II}]}/I_{\mathrm{CO}}$, in the central region of M31 as a function of the velocity resolution, δv, for the undetected CO emission (from Mochizuki [2004]). The open circles connected by dashed and dotted curves correspond to the two LWS beams (Mochizuki 2000) located at the positions with offsets of $50''$ and $100''$ from the galactic nucleus along the galactic major axis to the northeast, respectively. The filled circles connected by a solid curve indicate the average for the two LWS beams. The thick dot-dashed lines indicate the average ratios observed in the Large Magellanic Cloud (Mochizuki et al. 1994; Cohen et al. 1988) and starburst galaxies (Stacey et al. 1991). The thin dot-dashed lines indicate the standard deviation in the Magellanic Cloud ratio relative to the average.

ter were reproduced by the model clouds with sufficiently high column densities ($N_{\mathrm{H}} \gtrsim 10^{22}$ cm^{-2} of hydrogen nuclei) when the soft interstellar radiation field due to the Galactic bulge is taken into account. On the other hand, the higher M31 ratios are obtained only when $N_{\mathrm{H}} \lesssim 10^{21}$ cm^{-2}, under the equally soft incident radiation. At such a lower column density, the model cloud is translucent for photons sufficiently energetic to heat the grains but not sufficiently energetic to heat the gas ($h\nu \sim 1$ eV). This is a likely mechanism causing the relatively high $I_{[\mathrm{C\,II}]}/\nu I_\nu(100\ \mu\mathrm{m})$ ratios in the central region of M31 having a bright bulge; a typical column density of the neutral ISM between illuminating sources at $h\nu \sim 1$ eV is $N_{\mathrm{H}} \lesssim 10^{21}$ cm^{-2} in the region.

(b) [C II]/CO Line Ratio

In the ISM with its lower column density, CO line emission would be significantly affected because the species are present in deeper cloud regions (Figure 1). Mochizuki (2004) observed the inner part of M31 on a scale of one kiloparsec in the ^{12}CO J = 1–0 line, and obtained a lower limit for the [C II]/CO J = 1–0 integrated line intensity ratio of $I_{[\mathrm{C\,II}]}/I_{\mathrm{CO}} > 1.3 \times 10^4$ (3.3σ) assuming a velocity width of $\lesssim 300$ km s^{-1} for the undetected CO emission (Figure 3). This is higher than the ratios in starburst galaxies ($I_{[\mathrm{C\,II}]}/I_{\mathrm{CO}} \simeq 4 \times 10^3$; Stacey et al. 1991), in spite of the low recent star-forming activity in the inner part of M31.

Moreover, the ratio in the M31 center is comparable to, or higher than, those in irregular galaxies ($I_{[\mathrm{C\,II}]}/I_{\mathrm{CO}}$ = 1–5 $\times 10^4$; Figures 3 and 4). The unusually high ratios in these low-metallicity systems are ascribed to the expected low dust abundances, which allow CO-dissociating UV photons to penetrate deep into the molecular clouds (Maloney & Black 1988). In contrast, the inner part of the spiral galaxy M31 has a higher metallicity than the solar neighborhood (Blair, Kirshner, & Chevalier 1982); the region is the first example of an extremely high [C II]/CO J = 1–0 line ratio exceeding 10^4 in the main part of a galaxy with a metallicity not less than the solar-neighborhood value.

A comparison of the observations with PDR models showed that CO molecules are mostly photodissociated in the observed region because the neutral ISM is not sufficiently opaque to protect the species against the incident UV radiation, i.e., the weakness of the CO J = 1–0 emission is not ascribed to an insufficient excitation of the corresponding transition. This result is consistent with the low column density of the neutral ISM between illuminating sources ($N_{\mathrm{H}} \lesssim 10^{21}$ cm^{-2}) previously derived from the FIR line-to-continuum ratio of $I_{[\mathrm{C\,II}]}/\nu I_\nu(100\ \mu\mathrm{m})$, although the $I_{[\mathrm{C\,II}]}/\nu I_\nu(100\ \mu\mathrm{m})$

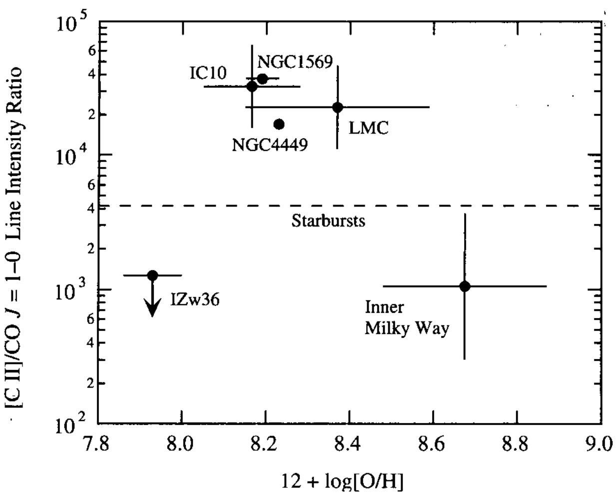

Fig. 4.— Observed [C II]/CO $J = 1$–0 line intensity ratio of galaxies (filled circles) plotted as a function of the interstellar oxygen abundance, 12 + log[O/H] (from Mochizuki & Onaka [2001]; see also references therein). The ratio for I Zw 36 (a blue compact dwarf galaxy, not an irregular) indicates the upper limit. The horizontal bars indicate the observation uncertainties for I Zw 36 and NGC 1569. For the inner Galaxy, the LMC, and IC 10, the horizontal and vertical bars represent the spatial variations within the galaxies. The dashed line indicates the upper limit for starburst and normal spirals (Stacey et al. 1991).

and $I_{[\mathrm{C\,II}]}/I_{\mathrm{CO}}$ ratios are sensitive to different energy ranges ($h\nu \sim 1$ eV and ~ 10 eV, respectively) of the illuminating radiation.

The expected low column density could be related to the low activity of the current star formation in the region. The neutral ISM can be more mixed with UV sources in the region than in the disks of gas-rich spirals, because the neutral ISM without large concentrations such as molecular cloud complexes (e.g., Loinard et al. 1999; Cram, Roberts, & Whitehurst 1980; Haas et al. 1998) is illuminated by the UV field due to evolved low-mass stars (e.g., Brown et al. 1998) in the former. Extremely high $I_{[\mathrm{C\,II}]}/I_{\mathrm{CO}}$ ratios without low metallicities could be an indicator for such conditions; similar ratios might be obtained toward the central regions of a certain category of other galaxies with suspended star-formation activity. This is in contrast to the widely accepted tendency that the $I_{[\mathrm{C\,II}]}/I_{\mathrm{CO}}$ ratio traces the galactic star-forming activity.

IV. SUMMARY

The central one-kiloparsec regions of spiral galaxies can show unexpected anomalies in the [C II] emission, which is frequently considered to trace intense interstellar UV radiation enhanced by recent star-forming activity in galaxies. Since the [C II] emission is one of the brightest galactic lines, more observations related to this topic should be carried out for understanding the anomalies in order also to interpret future observations of more distant unresolved galaxies correctly.

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