PASJ: Publ. Astron. Soc. Japan **58**, 753–757, 2006 August 25

[C I] 809 GHz Imaging of the NGC 6334 Complex

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(Received 2005 September 20; accepted 2006 May 21)

Abstract

We present Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) observations of submillimeter emissions from the NGC 6334 complex for both the ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ fine-structure line of atomic carbon and the ^{12}CO $J = 4 \rightarrow 3$ rotational transition of CO. We detected strong ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ emission from the entire star-forming NGC 6334 complex, and present maps of ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ emission and ^{12}CO $J = 4 \rightarrow 3$ emission. Comparing these maps with archival ASCA data, we show that, to the south of NGC 6334, the [C I] emissions are likely to be associated with strong X-ray emissions from the FIR sources. However, the calculation using the X-ray dissociation region model shows that the majority of the [C I] emission can not arise from X-ray dissociation of the cloud. Alternatively, far-ultraviolet radiation produced in the photodissociation regions is expected to contribute to dissociate the carbon monoxide in the NGC 6334 complex.

Key words: ISM: dissociation regions — ISM: lines — submillimeter: lines

1. Introduction

NGC 6334 is a star-forming molecular cloud complex at a distance of 1.7 kpc in the southern sky. It lies at $l = 351\overset{\circ}{.}42$, $b = 0\overset{\circ}{.}65$ and the extent of the optical nebulae (Rodgers et al. 1960) is $30' \times 60'$ across. This complex has drawn much attention, and has been investigated at various wavelengths. For instance, McBreen et al. (1979) mapped this nebula at 40–250 μm wavelengths and found five sites of massive star formation. They initially named these FIR sources using Roman numerals I–V. Harvey and Gatley (1983) and Loughran et al. (1986) designated additional FIR sources as I(N) and I(E).

Moran and Rodriguez (1980) found water masers in the NGC 6334 complex, and Gaume and Mutel (1987) followed by finding OH masers. Rodriguez, Canto, and Moran (1982) received credit for extensively observing NGC 6334 with the Very Large Array (VLA) at radio wavelengths, and the radio continuum sources were named as A–F. The effects of active star formation in the early stages were captured. Molecular outflows (Fischer et al. 1982; Bachiller, Cernicharo 1990) and shocked H_2 emission (Straw, Hyland 1989) were shown to have arisen during the star-formation process. Kraemer, Jackson, and Lane (1998) observed the NGC 6334 complex in the ionized carbon [C II] 158 μm and neutral oxygen lines [O I] 145 μm and [O I] 63 μm. As Jackson and Kraemer (1999) argued, the relative distribution of photodissociated regions traced by these lines is generally correlated with molecular gas. The SPIREX imaging of the NGC 6334 complex revealed the complex structure of the PAH emission and showed that the PAH emission in the complex is well correlated with the 158 μm line emission (Burton et al. 2000).

Of particular interest is that strong X-ray emissions from the NGC 6334 complex are associated with FIR sources I–V (Sekimoto et al. 2000). Young massive stars and low-mass pre–main-sequence stars (PMSs) in the FIR cores may produce the observed hard X-rays, which can ionize the inner part of the molecular cloud cores. As Silk and Norman (1983) and Krolik and Kallman (1983) suggested, the PMSs in the molecular cloud may have regulated the evolution of the molecular cloud and the star-formation rate in the NGC 6334 complex, since high-energy X-rays can penetrate much deeper into gas clouds than ultraviolet (UV) photons; also, X-ray irradiated gas has quite different chemical and thermal structures from that of a UV-irradiated cloud or a shocked cloud (Maloney et al. 1996).

In this paper, we present maps of the massive, southern star-forming region of the NGC 6334 complex in the [C I] 809 GHz and CO $J = 4$–3 transitions. These lines were observed with the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) located at Amundsen-Scott South Pole Station. We found two high-excitation CO and [C I] components on either side of the X-ray emission peak mapped with ASCA (Sekimoto et al. 2000). We discuss the physical parameters of gas clouds around star-forming sites in the NGC 6334 and the photodissociation/X-ray dissociation contributions for the atomic carbon emissions in these high-mass star-forming regions. The results and analysis are reported in section 3.

2. Observations

Observations were carried out with the AST/RO, located at Amundsen-Scott Station. AST/RO is a 1.7 m diameter, offset Gregorian telescope capable of observing at wavelengths of between 200 μm and 1.3 mm (Stark et al. 2001). The 809 GHz [C I] emission and 806 GHz $J = 4 \rightarrow 3$ ^{12}CO emission of the NGC 6334 complex were observed from May to July in 2000.

The emissions from the 809.34197 GHz $^3P_2 \rightarrow {}^3P_1$ line of

[C I] and the 806.6517 GHz $J = 7 \rightarrow 6$ transition of ^{12}CO were mapped at a 1′ spacing and a beam size of 60″, with an integration time of about 3 minutes per selected position. The atmosphere-corrected system temperature, $T^*_{\rm sys}$, was typically 15000 K and the receiver temperature was about 950–1050 K. The 461.041 GHz $J = 4 \rightarrow 3$ transition of ^{12}CO was observed simultaneously, with a beam size of 108″, a receiver temperature of 200–300 K, and an atmosphere-corrected system temperature of $T^*_{\rm sys} \sim 3600$ K at 461GHz. AST/RO suffered pointing errors on an order of approximately 1′ while the observations were made. The spectra were acquired in the position-switching mode.

The spectrometer used in both cases was a 2048-channel AOS with 1 MHz FWHM filters with 0.5 MHz separation (Schieder et al. 1989). The main beam telescope efficiency for both receivers was about 70%, as estimated from skydip measurements. The spectra were calibrated to the $T^*_{\rm R}$ antenna temperature scale, as described in Stark et al. (2001). To determine the atmospheric opacity and sky temperature, we used data from the NRAO-CMU 350 μm tipper in operations at the South Pole. Several times each hour, this instrument made a calibrated skydip using a broadband room-temperature bolometer. During the subsequent observing season, when the automated calibration system was working, it was determined that the opacity in the narrow 806 GHz band was related to the opacity measured by the NRAO-CMU tipper through the following relation (R. A. Chamberlin, private communication):

$$\tau_{806\,\rm GHz} = 1.82\,\tau_{\rm NRAO\text{-}CMU} - 1.51. \qquad (1)$$

We used this relation, together with the NRAO-CMU tipper data and thermometer measurements of the outside ambient temperature, to calculate the $T_{\rm sky}$ value. The intensity calibration errors were estimated to be ±15%. The data were calibrated and edited in COMB, as described in Stark et al. (2001).

3. Results and Analysis

3.1. [C I] 809 GHz Emission of NGC 6334

Figure 1 shows the spatial distribution of [C I] 809 GHz emissions along the ridge of the NGC 6334 complex. The distribution of the [C I] 809 GHz emission is quite similar to that of the [C I] 492 GHz emission of NGC 6334 (M. Yan et al. in preparation). The [C I] ^{3}P$_2 \rightarrow {}^3$P$_1$ transition at 809.3432 GHz (370.4145 μm) and the [C I] ^{3}P$_1 \rightarrow {}^3$P$_0$ transition at 492.1612 GHz (609.1347 μm) arise from magnetic-dipole transitions between adjacent levels of the ^{3}P ground state of neutral atomic carbon. The [C I] 809 GHz emission extends over the map with a patchy distribution, and it is not restricted to regions adjacent to the H II regions and sites of massive star formation. The overall distribution of the submillimeter [C I] fine structure line is somewhat similar to those of the submillimeter CO emission lines, ^{12}CO $J = 7 \rightarrow 6$ and ^{12}CO $J = 4 \rightarrow 3$ (figure 2).

The [C I] 809 GHz emission map consists of northern and southern clouds. The mid-J CO excitation lines behave in the same manner as the [C I] 809 GHz emission. The peak emission of the northern cloud in the [C I] 809 GHz emission (figure 1) is displaced slightly from the peak emission of the

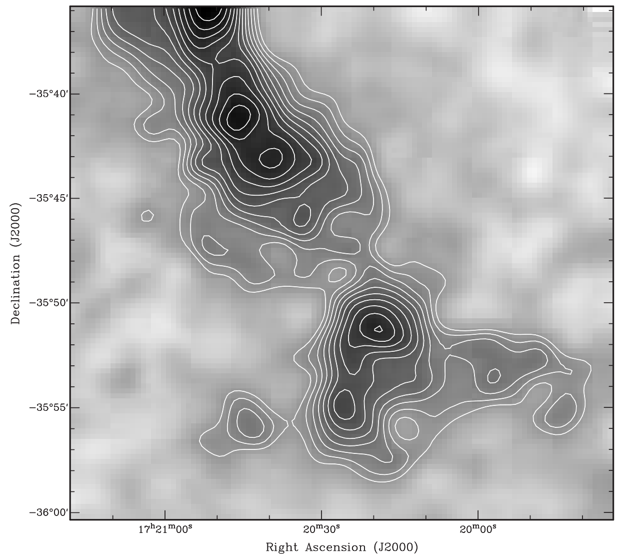

Fig. 1. Contour image of ^{12}[C I] ^{3}P$_2 \rightarrow {}^3$P$_1$ emission from NGC 6334 observed with the AST/RO telescope. Contours are at $\int T^*_{\rm A}(^{12}[{\rm C\,I}]\ ^3{\rm P}_2 \rightarrow {}^3{\rm P}_1)\,dv$ = 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, and 27 K km s^{-1}.

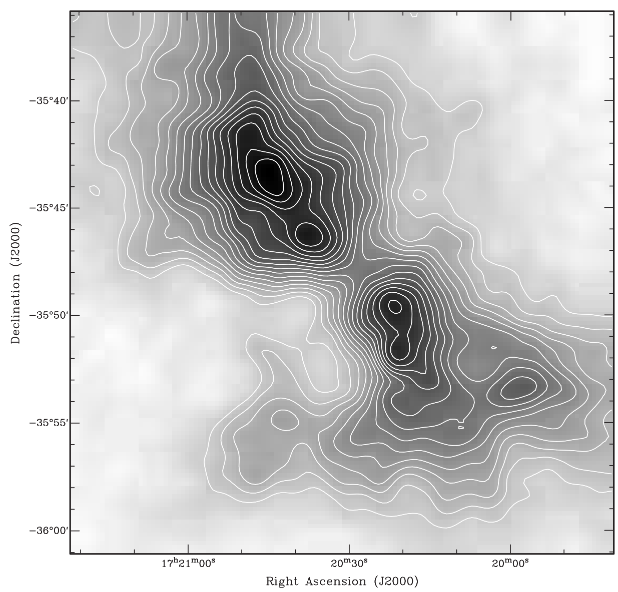

Fig. 2. Contour image of ^{12}CO $J = 4 \rightarrow 3$ emission from NGC 6334.

northern cloud in the ^{12}CO $J = 4 \rightarrow 3$ emission. Within the range of the pointing error, the northern peak of the [C I] 809 GHz emission is unlikely to be associated with star-forming cores I and II (figure 3). Unlike the northern cloud in the [C I] 809 GHz emission map, the peak of the southern cloud in the [C I] 809 GHz emission coincides with the peak of the southern cloud in the ^{12}CO $J = 4 \rightarrow 3$ emission, and might be associated with star-forming cores IV and V.

Within the range of the calibration error, the luminosity of the ^{12}CO $J = 7 \rightarrow 6$ emission line integrated over the source is about 1.2×10^{37} erg s^{-1} and that of the ^{12}CO $J = 4 \rightarrow 3$ emission is approximately 1.4×10^{37} erg s^{-1}. Using the luminosities

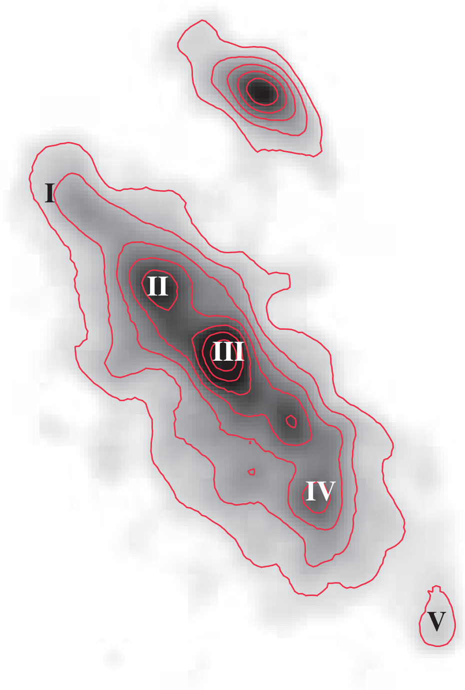

Fig. 3. ASCA image of the NGC 6334 complex. FIR sources are marked as Roman numerals.

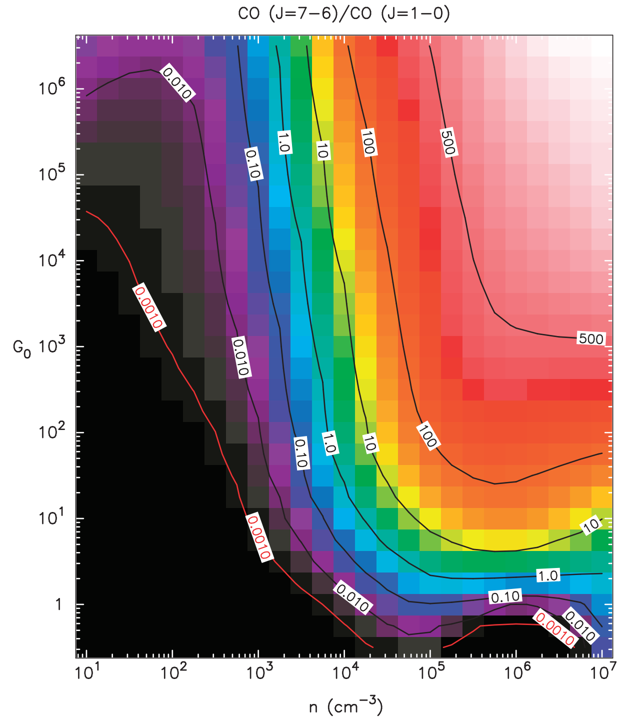

Fig. 4. Line ratios of the ^{12}CO $J = 7 \rightarrow 6$ and $J = 1 \rightarrow 0$ spectra observed with AST/RO plotted against an estimate of the cloud density n and incident FUV flux G_0, obtained using the PDR model.

of the CO $J = 1 \rightarrow 0$, $J = 2 \rightarrow 1$, and $J = 3 \rightarrow 2$ transitions (Kraemer, Jackson 1999), the lower limit of the total CO rotational line cooling is $L^{\rm tot}_{\rm CO} \approx 7.3 \times 10^{37}$ erg s^{-1} within the range of the calibration error. The ^{12}CO $J = 7 \rightarrow 6$ transition contributes at most 15% of the total CO luminosity. On the other hand, we calculated the lower limit of the [C I] 809 GHz line cooling to be $L_{\rm C\,I} \approx 4.5 \times 10^{36}$ erg s^{-1} from the NGC 6334 complex. Using the line ratio of the ^{12}[C I] ^{3}P$_2 \rightarrow {}^3$P$_1$ and ^{12}[C I] ^{3}P$_1 \rightarrow {}^3$P$_0$ emission lines ($\approx$ 0.6–0.7, Tieftrunk et al. 2001), we estimate that the total observed [C I] line cooling was $L^{\rm tot}_{\rm [C\,I]} \approx 1.1 \times 10^{37}$ erg s^{-1}. The total estimated energy released by the [C I] fine-structure lines from the NGC 6334 complex is similar to the energy released by the ^{12}CO $J = 7 \rightarrow 6$ transition, and hence is much smaller than the total energy released by all CO transitions. However, the luminosity carried by the [C II] line is at least 1000-times higher than the total cooling by all CO and [C I] transitions. This estimate suggests that the CO rotational cooling lines and [C I] transitions lines are less dominant coolants in the molecular and atomic ISM of the NGC 6334 complex.

The CO $J = 7 \rightarrow 6$ emission traces the warm and dense molecular gas where collisional de-excitation balances the radiative de-excitation (Spitzer 1978; Hollenbach, Tielens 1999). This can occur when the far-ultraviolet (FUV) photons from stars photo-dissociate the molecular cloud (Tielens, Hollenbach 1985; Sternberg, Dalgarno 1989; Wolfire et al. 1990; Hollenbach, Tielens 1999).

We attempted to estimate the cloud density, kinetic temperature, and FUV fluxes of the gas (Tielens, Hollenbach 1985; Sternberg, Dalgarno 1989; Wolfire et al. 1990; Sternberg, Dalgarno 1995) with the PDR model (Wolfire et al. 1990) using our newly observed line ratios of the ^{12}CO $J = 7 \rightarrow 6$ and ^{12}[C I] ^{3}P$_2 \rightarrow {}^3$P$_1$ emissions together with ^{12}CO $J = 1 \rightarrow 0$ (Kraemer, Jackson 1999) and [O I] 63 μm, 145 μm (Kraemer et al. 1998). However, the current PDR model failed to fit the observed intensity ratios. The line ratio of ^{12}CO $J = 7 \rightarrow 6/^{12}$CO $J = 1 \rightarrow 0$ with the PDR model calculation (figure 4) by M. Wolfire (2005, private communication) suggests only the lower limit of the cloud density, $n_{\rm H_2}$, to be 10^3 cm^{-3}, and the incident FUV flux, G_0, to be 1 in the CO zone. G_0 is in units of the local interstellar value of 1.6×10^{-3} erg cm^{-2} s^{-1} (Habing field). The observed line ratios of ^{12}CO $J = 7 \rightarrow 6/^{12}$CO $J = 1 \rightarrow 0$ for NGC 6334 II, III, IV sources (figure 3) are similar to 0.1 ± 0.1. Kraemer, Jackson, and Lane (1998) also reported that they were not able to fit the PDR model to their observed [C II] 158 μm, [O I] 63 μm, and [O I] 145 μm line ratios for these sources. The failure of the above PDRs model is likely to be due to fitting the gas to a single PDR model, which assumes the gas to be homogeneous.

Alternatively, we examined the effect of X-ray emissions on submillimeter emissions from NGC 6334 in both the ^{12}[C I] ^{3}P$_2 \rightarrow {}^3$P$_1$ fine-structure line of atomic carbon and the ^{12}CO $J = 7 \rightarrow 6$, $J = 4 \rightarrow 3$ rotational transitions of CO. X-rays induce the ionization of atomic and molecular species in an X-ray irradiated cloud, and change the chemical structure of the irradiated cloud. Therefore, the abundance of the gas-phase species, grain chemistry, and the X-ray intensity characterize the chemical structure of an X-ray irradiated cloud. In order to investigate the effects of X-rays on the photoionization of the molecular cloud core in the southern part of the NGC 6334

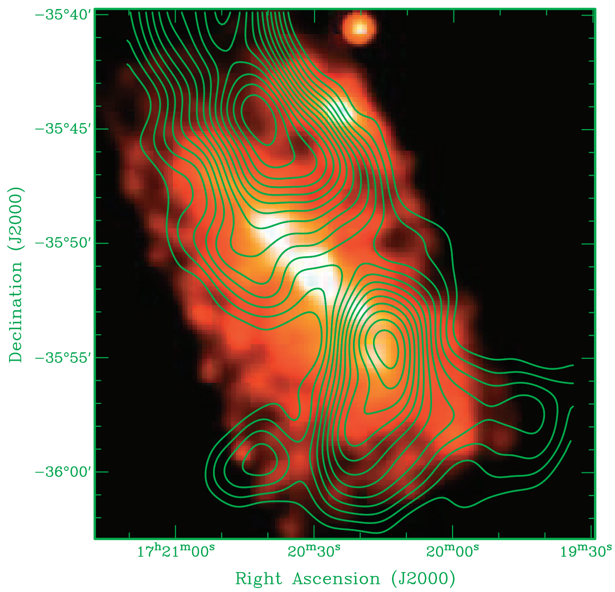

Fig. 5. Contour image of ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ emission overlaid on the X-ray emission observed with the ASCA satellite of hard X-rays from far-infrared (FIR) star clusters in the giant molecular cloud (GMC) cores of the NGC 6334 star-forming region. We have retrieved all archival ASCA observations of the NGC 6334 complex.

complex, we calculated the X-ray induced ionization rate in the molecular cloud. As shown in figure 5, the ASCA X-ray observations reveal bright diffuse X-ray sources in the NGC 6334 complex. For a comparison, we retrieved all of the ASCA observations of NGC 6334. The X-ray sources are associated with the FIR star clusters in the molecular cloud cores in the NGC 6334 complex. In general, the southern ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ emitting clouds in NGC 6334 can be matched with locally enhanced X-ray emission arising from the FIR source, IV (figure 5). The X-ray luminosity of source IV is about $1.75 \pm 0.1 \times 10^{33}$ erg s^{-1} and is at least 10^3 times that of typical low-mass PMSs (Sekimoto et al. 2000).

The ionization rate by X-rays (ζ_X) throughout the cloud core can be observed using

$$\zeta_X = 1.4 \times 10^{-18}\,\mathrm{s}^{-1} \frac{L_X}{10^{33}\,\mathrm{erg\,s}^{-1}} \frac{1\,\mathrm{pc}^2}{r_X^2} \frac{10^{22}\,\mathrm{cm}^{-2}}{N_H}, \quad (2)$$

where L_X is the X-ray luminosity near the [C I]-emitting cloud core and r_X is the distance from the X-ray source to the [C I]-emitting cloud core (Maloney et al. 1996). Since we were studying the effects of an increase of the ionization rate due to X-rays on the observed [C I] cloud, the total ionization rate due to X-rays, ζ_X, was derived to be about 10^{-17} s^{-1} within a radius of $r_X \approx 0.4$ pc from the X-ray source, IV, in the NGC 6334 complex. The total ionization rate per particle due to X-rays, ζ_X, is proportional to the local X-ray energy deposition rate per particle, H_X, as $H_X \approx (1/3) \times 10^{-10} \zeta_X$. Parameter H_X divided by the gas density, n, H_X/n, determines the physical and chemical states of an X-ray irradiated molecular cloud. Using the observed value of ζ_X and the relationship between H_X/n and ζ_X, we calculated $H_X/n = 3.3 \times 10^{-33}$ to 3.3×10^{-31} erg s^{-1} for gas densities of 10^5 cm^{-3} and 10^3 cm^{-3}. For $H_X/n > 10^{-26}$ erg s^{-1}, the [C I] fine-structure line is a major coolant in the X-ray irradiated cloud. Maloney, Hollenbach, and Tielens (1996) presented their model results for only $H_X/n = 3.8 \times 10^{-30}$ to 3.8×10^{-25} erg s^{-1}. For $H_X/n < 3.8 \times 10^{-25}$ erg s^{-1}, there is a rapid decrease in the abundance of atomic carbon, which results in a decreased brightness for the ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ line. Therefore, we are able to conclude that this [C I] 809 GHz emission arises predominantly from photodissociation regions (PDRs) owing to ultraviolet radiation from the star-formation sites rather than X-ray dissociation regions (XDRs), although we were not able to fit the observed line ratios using a single PDR model.

4. Summary and Conclusion

We presented the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) observations of submillimeter emissions from the NGC 6334 complex, in both the ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ fine-structure line of atomic carbon and the ^{12}CO $J = 4 \rightarrow 3$ rotational transition of CO. We detected strong ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ emission from the entire star-forming NGC 6334 complex and produced maps of ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ and ^{12}CO $J = 4 \rightarrow 3$ emissions. Comparing these maps with the archival ASCA data, we note that south of the NGC 6334 complex, the peak of the ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ emission is likely to be associated with hard X-rays from the far-infrared cluster, IV, since the ^{12}[C I] $^3P_2 \rightarrow {}^3P_1$ and $^3P_1 \rightarrow {}^3P_0$ structure lines of atomic carbon are the dominant coolants in the X-ray dissociated cloud (Maloney et al. 1996). However, the calculation using their X-ray dissociation regions (XDRs) model shows that the majority of the [C I] emission can not arise from the X-ray dissociation of the cloud. Alternatively, far-ultraviolet (FUV) produced in the atomic gas is expected to contribute to dissociate the carbon monoxide in the NGC 6334 complex.

We thank Adair P. Lane, Antony A. Stark, and Chris Martin for their support to this project. We thank anonymous referee for his/her helpful comments for improving this manuscript. We thank Mark Wolfire and Marc Pound for figure 4. SK was supported in part by Korea Science & Engineering Foundation (KOSEF) under a cooperative agreement with The Astrophysical Research Center of the Structure and Evolution of the Cosmos (ARCSEC).

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