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A Multitransition CO Study in the 30 Doradus Complex in the Large Magellanic Cloud

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ABSTRACT. We have made a multitransition CO study of the largest H II complex, the 30 Doradus nebula, in the Large Magellanic Cloud (LMC). This is the most luminous example of a starburst region in the Local Group. We have searched for ^{12}CO $J = 7 \rightarrow 6$ emission toward the 30 Doradus complex with the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO), located at 2847 m altitude at the Amundsen-Scott South Pole Station. As a result, we have detected a ^{12}CO $J = 7 \rightarrow 6$ emitting cloud near the 30 Doradus complex. The ^{12}CO $J = 7 \rightarrow 6$/^{12}CO $J = 4 \rightarrow 3$ line temperature ratio in this region is approximately a factor of 2 higher than that observed near the Sgr B2 complex. A radiative transfer calculation using the line ratios shows that the core of massive star formation in the LMC is much warmer and denser than that of the Milky Way.

Online material: color figure

1. INTRODUCTION

Technological advances of submillimeter-wave and far-infrared (FIR) spectroscopy have made it possible to provide resources for understanding the physical conditions and the chemistry of atomic and molecular clouds in the interstellar medium (ISM) in external galaxies. Submillimeter-wave and FIR cooling lines are the dominant sources of cooling in the ISM and are therefore crucial to understanding the physical and chemical processes of star formation in the ISM.

At a distance of 55 kpc (Feast 1991), the Large Magellanic Cloud (LMC) can be mapped with a high spatial resolution in high-J excitation of ^{12}CO lines by the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO). The LMC presents us with a unique opportunity to study the interaction of massive stars and their interstellar environment, since the stars in the LMC are at a common distance and are close enough that individual stars and their parental clouds can be studied in great detail. The LMC also provides an opportunity to study the effects of different far-UV radiation from stars on their natal interstellar clouds in a low-metallicity environment. The giant H II complex 30 Doradus in the LMC extends for more than 100 pc and has revealed a very complicated velocity structure (Chu & Kennicutt 1994). The *ROSAT* High Resolution Imager (HRI; Wang 1999) and recent studies from *Chandra* observations (Lazendic et al. 2003; L. Townsley et al. 2005, in preparation) have proven that there are hot gas associated with the entire giant H II complex.

In this paper, we report the first detection of ^{12}CO $J = 7 \rightarrow 6$ emission in the LMC arising from the X-ray–bright giant H II complex 30 Doradus. We examine the physical properties of its emitting gas in the LMC and present an analysis of density, temperature, and excitation conditions using the radiative transfer analysis.

2. OBSERVATIONS

The data were taken with AST/RO, a 1.7 m diameter offset Gregorian telescope. AST/RO is located at 2847 m altitude at the Amundsen-Scott South Pole Station and is capable of observing at wavelengths between 200 μm and 1.3 mm (Stark et al. 2001). This site is very dry, and thus very good for submillimeter observations (Chamberlin et al. 1997).

The receiver used was a dual-channel superconductor-insulator-superconductor (SIS) waveguide receiver (Walker et al. 1992; Honingh et al. 1997) for simultaneous 461–492 and 807 GHz observations. Two acousto-optical spectrometers (AOSs; Schieder et al. 1989) were used as back ends. The AOSs had a 1.07 MHz resolution and 0.75 GHz effective bandwidth, resulting in a velocity resolution of 0.65 km s^{-1} at 461 GHz and 0.37 km s^{-1} at 807 GHz. The data were smoothed to a uniform velocity resolution of 1 km s^{-1}. The high-frequency observations were made with the ^{12}CO $J = 7 \rightarrow 6$ line in the lower sideband (LSB). Since the intermediate frequency of the AST/RO system is 1.5 GHz, the $^3P_2 \rightarrow {}^3P_1$ line of the [C I] line appears in the upper sideband (USB) and is superposed on the observed LSB spectrum. The local oscillator frequency was chosen so that the nominal line centers appear separated by 100 km s^{-1} in the double-sideband spectra. A third AOS, used for only a few spectra, had a 0.031 MHz resolution and a 0.25 GHz bandwidth. Atmosphere-corrected system temperatures ranged between 320 and 390 K at 461–492 GHz, and from 1050 to 1190 K at 807 GHz. Telescope efficiency η_ℓ, estimated using Moon scans, sky dips, and measurements of the beam-edge taper, was 81% at 461–492 GHz, and 71% at 807 GHz.

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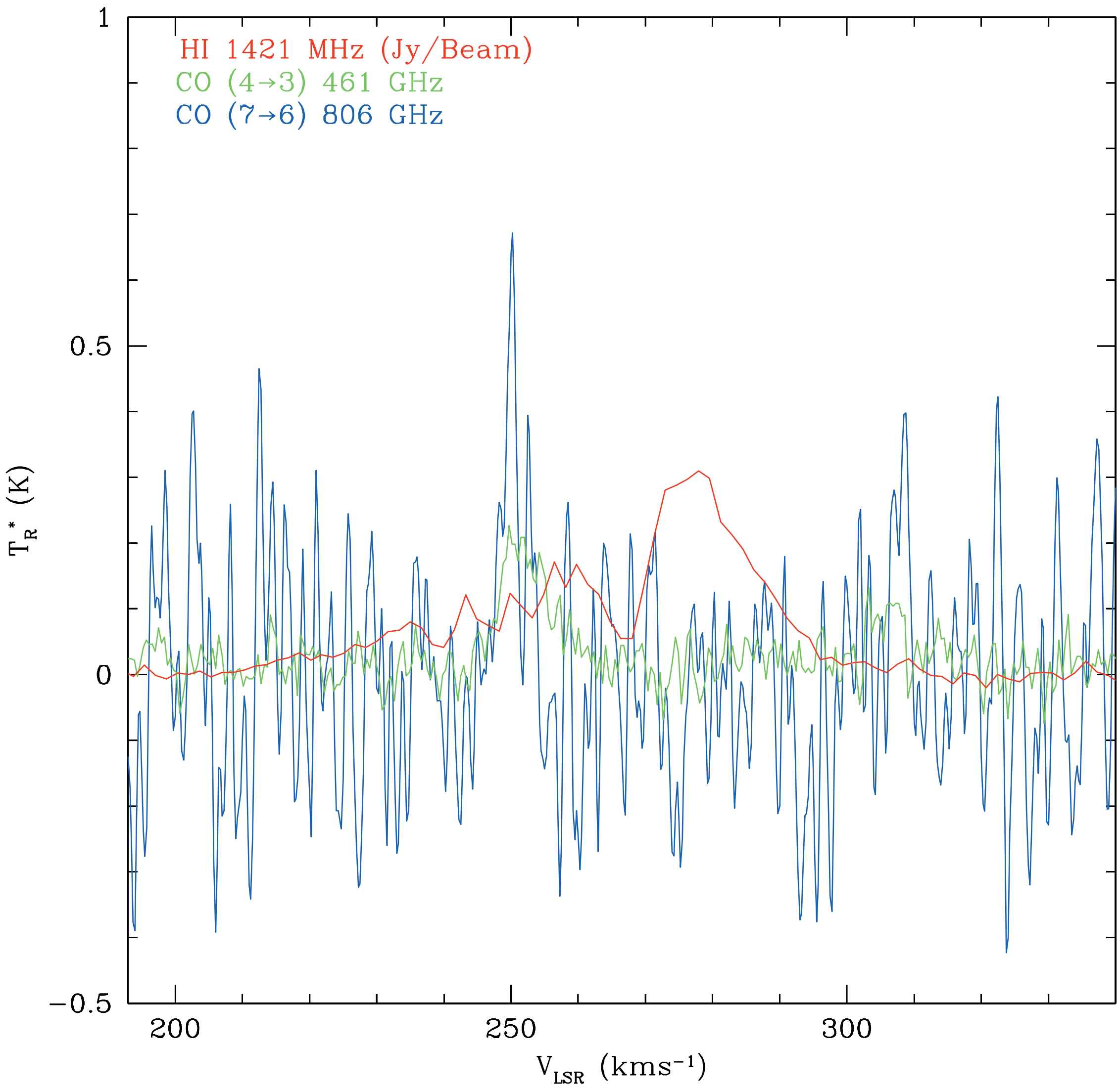

FIG. 1.—Comparison of ^{12}CO $J = 7 \rightarrow 6$ emission line and the ^{12}CO $J = 4 \rightarrow 3$ emission line from this position. The brightness temperature of the ^{12}CO $J = 7 \rightarrow 6$ emission is divided by 0.55. The H I spectrum of this position is overlaid as a dashed line. The unit of H I emission is in Jy beam^{-1}.

Emission from the ^{12}CO $J = 7 \rightarrow 6$ lines at 806.6517 GHz was detected at R.A. = $5^h38^m39\overset{s}{.}8$, decl. = $-69°03'21''$ (J2000.0), corresponding to R.A. = $5^h39^m00^s$, decl. = $-69°04'53\overset{''}{.}44$ (B1950.0). A region of about $5' \times 5'$ was mapped, with a grid spacing of $1'$ and a beam size of $58''$. Observing time at this position was about 20 minutes. The standard chopper wheel calibration technique was employed, implemented at AST/RO by way of regular observations (every few minutes) of the sky and two blackbody loads of known temperature (Stark et al. 2001). Atmospheric transmission was monitored by regular sky dips, and known bright sources were observed every few hours. The intensity calibration errors were estimated to be $\pm 30\%$.

3. RESULTS

We detect ^{12}CO $J = 7 \rightarrow 6$ line emission at R.A. = $5^h38^m39.8^s$, decl. = $-69°03'21''$ (J2000.0) in the LMC (Fig. 1). This position is found to be between the areas labeled 30Dor-6 and 30Dor-10 in Johansson et al. (1998), the northwestern edge of the CO cloud associated with the main northern ionization front in 30 Doradus. Both ^{12}CO $J = 7 \rightarrow 6$ and ^{12}CO $J = 4 \rightarrow 3$ emissions appear at $V_{LSR} = 249.6$ km s^{-1}. This systemic velocity is similar to that of the ^{12}CO $J = 1 \rightarrow 0$ emission $V_{LSR} = 249.5$ km s^{-1} obtained by the 4 m NANTEN telescope (Fukui et al. 1999; Mizuno et al. 2001), and $V_{LSR} = 249.4$ km

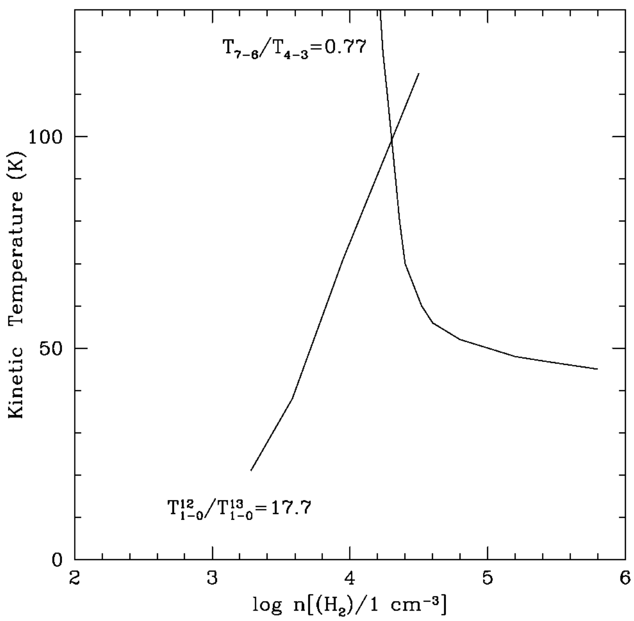

FIG. 2.—LVG model result for observed line ratios of ^{12}CO $J = 4 \rightarrow 3$/^{12}CO $J = 7 \rightarrow 6$ and ^{12}CO $J = 1 \rightarrow 0$/^{13}CO $J = 1 \rightarrow 0$ as a function of the total molecular hydrogen volume density for different values for the gas kinetic temperature by assuming a ^{13}CO/^{12}CO abundance ratio of about 50. [*See the electronic edition of the PASP for a color version of this figure*.]

s^{-1} of 30Dor-6 by SEST (Swedish-European Submillimeter Telescope; Johansson et al. 1998). However, the [C I] 809 GHz emission line is not seen. An upper limit for the [C I] 809 GHz emission integrated intensity is approximately 0.76 ± 0.2 K km s^{-1}. The upper limit is defined by 3 σ rms noise, and the rms noise in the integrated intensity of a nondetected region was calculated by $(n_{\rm chan})^{1/2}\, \Delta v_{\rm chan} T_{\rm rms}$, where $n_{\rm chan}$ is twice the FWHM of the line in numbers of channels, and Δv is the channel separation in km s^{-1}.

While the main-beam brightness temperature of ^{12}CO $J = 4 \rightarrow 3$ emission is bright, at $T_{\rm MB} = 0.197 \pm 0.05$ K, the main-beam brightness temperature of the ^{12}CO $J = 7 \rightarrow 6$ emission is approximately 0.152 K by fitting the Gaussian. The FWHM of the ^{12}CO $J = 7 \rightarrow 6$ emission line is about 7 km s^{-1}, and its integrated intensity is about 1.14 ± 0.5 K km s^{-1}. An inspection of Figure 1 shows that both ^{12}CO $J = 7 \rightarrow 6$ and ^{12}CO $J = 4 \rightarrow 3$ profiles might have redshifted velocity components. The possible presence of ^{12}CO $J = 7 \rightarrow 6$ and ^{12}CO $J = 4 \rightarrow 3$ high-velocity components indicates the outflow in the relatively warm and dense molecular material (Cecchi-Pestellini et al. 2001; Zhang et al. 2001). While significantly weaker than the molecular outflow, the neutral H I gas shows high-velocity wings at the similar velocity of roughly 304 km s^{-1}. We note that this H I spectrum is found in region of very active star formation in the LMC, which therefore has a very complex ISM structure. In the aperture synthesis map of the neutral hydrogen gas in the LMC (Kim et al. 1998, 1999, 2003), this region displays a very complex small-scale structure, resulting from its high density, the presence of many clouds, and the complex pattern of star formation in this region. This complexity is illustrated by the multimodal line profile in this region, as shown in Figure 1.

The age of massive stars in this region is about 1–2 Myr (Massey & Hunter 1998), similar to the ages of young stars associated with molecular cloud complexes in the solar neighborhood (Hartmann et al. 2001). Since the kinematic age of an expanding H I shell surrounding this region is close to 10 Myr, and the product of preshock density and velocity is approximately $nv \sim 18$ cm^{-3} km s^{-1}, it is likely that the molecular clouds in this region might have formed by acceleration and accumulation of neutral clouds during the dynamical lifetime of the evacuated shell (Bergin et al. 2004).

4. DISCUSSION

In order to investigate the thermodynamic state of ^{12}CO $J = 4 \rightarrow 3$ and ^{12}CO $J = 7 \rightarrow 6$ emitting molecular gas, and to understand gas cooling by molecular radiation, we have undertaken a radiative transfer calculation using the "Sobolev" approximation (Rybicki & Hummer 1978). From the simplest approximations, such as local thermodynamic equilibrium models (LTEs), to more comprehensive numerical calculations, numerous radiative transfer models of molecular line formation have been developed in the past three decades. Models of the excitation and radiative transfer can be used to solve for the density, temperature, and cooling rate of the molecular gas. To avoid degeneracy in this solution, it is important to have observations of a line transition from a J state that is sufficiently high in energy such that it is only weakly populated. CO in interstellar molecular gas is typically in a thermodynamic state, in which the low-J transitions are in approximate thermal equilibrium, so that all of the rotational transitions below some J level have roughly the same excitation temperature as the $J = 1 \rightarrow 0$ transition.

The Sobolev approximation, which is known as a large-velocity gradient (LVG) radiative transfer analysis (Goldreich & Kwan 1974; Scoville & Solomon 1974), simplifies radiative transfer by assuming that an emitted spectral-line photon can only be absorbed "locally," within a small region whose velocity is similar to the point of emission. The LVG radiative transfer code by S. Kim and M. Yan simulates a plane-parallel cloud geometry and employs a modified escape probability formalism. It solves the equations of statistical equilibrium for the fractional population of CO rotational levels at each depth. It includes the lowest 30 rotational levels of the ground vibrational level and uses Einstein A values and H_2 impact rate coefficients of Balakrishnan et al. (2002). This LVG radiative transfer code has been implemented with a Java applet.[2] The solution of the radiative transfer calculation depends on the ratio of ^{12}CO to ^{13}CO abundance and the velocity gradient.

The line brightness temperature ratios of ^{12}CO $J = 4 \rightarrow 3$ to ^{12}CO $J = 7 \rightarrow 6$, together with ^{12}CO $J = 1 \rightarrow 0$ to ^{13}CO $J = 1 \rightarrow 0$ from the 30Dor-6 cloud (Johansson et al. 1998), allow us to estimate the kinetic temperature and the number density of molecular hydrogen $n(H_2)$ using the radiative transfer analysis (Fig. 2). The solution of the radiative transfer equation gives line ratios of ^{12}CO $J = 7 \rightarrow 6$ to ^{12}CO $J = 4 \rightarrow 3$ and ^{12}CO $J = 1 \rightarrow 0$ to ^{13}CO $J = 1 \rightarrow 0$ as a function of the total molecular hydrogen volume density for different values of the gas kinetic temperature. The abundance ratio ^{12}CO/^{13}CO is taken to be 50 (Israel et al. 2003) in the LMC. The velocity gradient of the CO $J = 7 \rightarrow 6$ emitting cloud is assumed to be about 1 km s^{-1} pc^{-1} at the distance of the LMC (Feast 1991) from a comparison of line widths and the spatial resolutions of the ^{12}CO $J = 1 \rightarrow 0$, ^{s13}CO $J = 1 \rightarrow 0$, ^{12}CO $J = 4 \rightarrow 3$, and ^{12}CO $J = 7 \rightarrow 6$ data. Here the depth-dependent gas temperature is calculated by assuming thermal equilibrium, $G(T) - L(T) = 0$, where $G(T)$ and $L(T)$ are the total heating and cooling rates, respectively (Sternberg & Dalgarno 1995).

The LVG model shows that this ^{12}CO $J = 7 \rightarrow 6$ emitting gas has a kinetic temperature of about 100 K and a mean molecular hydrogen volume density of $10^{4.3}$ cm^{-3} (Fig. 2). The ^{12}CO $J = 7 \rightarrow 6$/^{12}CO $J = 4 \rightarrow 3$ line temperature ratio in this region is approximately a factor of 2 higher than that observed near the Sgr B2 complex, the massive star-forming region in our Galactic center (Kim et al. 2002), and a factor of 4 higher than that observed in the nuclear region of the starburst galaxy M82 (Mao et al. 2000). The derived molecular hydrogen volume density of this warm, dense molecular cloud in the LMC is slightly higher than that of the Sgr B2 complex, but the kinetic temperature of this region is about a factor of 2 higher than that of the Sgr B2 complex. By comparison, the temperatures of two massive starburst regions in our Galactic center, the Sgr B2 and Sgr A complexes, are 72 and 47 K, respectively (Kim et al. 2002). The results of radiative transfer models are often reasonably accurate, even when the assumptions underlying the models are violated (Ossenkopf 1997). Therefore, from this study we find that the core of massive star formation in the LMC is much warmer and denser than that in the heart of the Milky Way.

[2] See http://arcsec.sejong.ac.kr/~skim/lvg.html.

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