DETECTION OF THE $^{13}$CO $J = 6 \rightarrow 5$ TRANSITION IN THE STARBURST GALAXY NGC 253

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ABSTRACT

We report the detection of $^{13}$CO $J = 6 \rightarrow 5$ emission from the nucleus of the starburst galaxy NGC 253 with the redshift ($z$) and Early Universe Spectrometer (ZEUS), a new submillimeter grating spectrometer. This is the first extragalactic detection of the $^{13}$CO $J = 6 \rightarrow 5$ transition, which traces warm, dense molecular gas. We employ a multiline LVG analysis and find $\approx 35\%$–$60\%$ of the molecular interstellar medium is both warm ($T \approx 110$ K) and dense ($n_{H_2} \approx 10^4$ cm$^{-3}$). We analyze the potential heat sources and conclude that ultraviolet and X-ray photons are unlikely to be energetically important. Instead, the molecular gas is most likely heated by an elevated density of cosmic rays or by the decay of supersonic turbulence through shocks. If the cosmic rays and turbulence are created by stellar feedback within the starburst, then our analysis suggests the starburst may be self-limiting.

Subject headings: galaxies: individual (NGC 253) — galaxies: ISM — galaxies: nuclei — galaxies: starburst — ISM: molecules — submillimeter

1. INTRODUCTION

NGC 253 is a nearby ($d \approx 2.5$ Mpc; Mauersberger et al. 1996), highly inclined ($i \approx 78^\circ$; Pence 1981) Sc galaxy undergoing a nuclear starburst (Rieke et al. 1988). The infrared (IR) luminosity in the central 30$''$ is $1.5 \times 10^{10}$ L$_{\odot}$ (Telesco & Harper 1980), and the mid-IR morphology indicates most of this emission arises from a 7$''$ region centered within 1$''$ of the 2 µm nucleus (Telesco et al. 1993). Near-IR images show a prominent stellar bar (Scoville et al. 1985) which likely plays a major role in channeling gas into the central starburst (Peng et al. 1996; Das et al. 2001). Estimates of the gas mass in the central $\approx 300$ pc are in the range $(0.4$–$4.2) \times 10^6$ M$_{\odot}$ (Krugel et al. 1990; Mauersberger et al. 1996; Harrison et al. 1999).

The $J = 6 \rightarrow 5$ and $7 \rightarrow 6$ transitions of CO arise from states with energy levels $\approx 110$, $\approx 120$ K, dense ($n_{H_2} \approx 4.5 \times 10^4$ cm$^{-3}$) molecular gas, most likely heated by cosmic rays injected into the interstellar medium (ISM) by the many supernovae ($\approx 0.1$ yr$^{-1}$; Ulvestad & Antonucci 1997). This model finds large optical depths in the mid-$J$ CO lines and thus predicts bright CO emission. To further constrain the excitation and energetics of the molecular gas, we observed the $^{12}$CO $J = 6 \rightarrow 5$ transition, which provides a strong constraint on the $^{12}$CO $J = 6 \rightarrow 5$ opacity. This is the first extragalactic detection of the $^{12}$CO $J = 6 \rightarrow 5$ transition, and the first detection of any $^{13}$CO transition greater than $J = 3 \rightarrow 2$ from beyond the Magellanic Clouds.

2. OBSERVATIONS

We observed $^{12}$CO $J = 6 \rightarrow 5$ ($433.56$ µm), $J = 7 \rightarrow 6$ ($371.65$ µm), $^{13}$CO $J = 6 \rightarrow 5$ ($453.50$ µm), and the [C I] $P_2 \rightarrow P_1$ fine-structure line ($370.41$ µm) toward NGC 253 in 2006 December with ZEUS (Stacey et al. 2004) at the Caltech Submillimeter Observatory (CSO) on Mauna Kea. ZEUS is a direct-detection grating spectrometer providing a slit-limited resolving power of $\lambda/\Delta \lambda \approx 1000$ across the 350 and 450 µm telluric windows. It currently uses a $1 \times 32$ semiconductor bolometer array oriented along the dispersion direction, with the pixel size approximately matched to a spectral resolution element. A pair of bandpass filters centered at 350 and 450 µm are mounted directly in front of the detector array, such that the system simultaneously provides a 16 pixel spectrum in both windows. The bandwidth is sufficiently large to observe $^{13}$CO $J = 7 \rightarrow 6$ and [C I].

We obtained absolute spectral calibration with observations of Orion (BN-KL) and flux calibration with observations of Saturn, which was assumed to have brightness temperatures of 116, 118, and 97 K at 434, 453, and 371 µm, respectively. We observed the four lines over the course of three nights in good submillimeter weather, with $T_{225\text{GHz}} = 0.04$–$0.06$. A zenith opacity was obtained from both $\tau_{225\text{GHz}}$ and $\tau_{350}$ using the CSO atmospheric transmission model, and the mean of the two values was used to calculate the transmission to the source. Observations of NGC 253 were centered at R.A. = $00^h47^m33.2^s$, decl. = $-25^\circ17'18''$ (J2000.0), and small maps in the $^{12}$CO lines verified that the beam was centered within 4$''$ of the CO emission peak. We used total power maps of Uranus to measure the FWHM of the beam to be 11$''$ at 434 and 453 µm and 10$''$ at 371 µm. All data were obtained by chopping and nodding the telescope with a 30$''$ throw. The spectra of $^{12}$CO $J = 6 \rightarrow 5$, $^{13}$CO $J = 6 \rightarrow 5$, and the $^{12}$CO $J = 7 \rightarrow 6$ and [C I] pair shown in Figure 1 represent total integrations times of 6, 70, and 5 minutes, respectively. A linear baseline is removed from all spectra, and the integrated intensities are listed in Table 1. In addition to the nuclear spectra, we obtained a simultaneous map in the $^{12}$CO $J = 7 \rightarrow 6$ and
We increase the CO-H2 collisional rate coefficients from these unresolved clouds, such that the absolute line intensities undergoing uniform collapse (Castor 1970; Goldreich & Kwan 1993) with, derived for a spherical cloud.

To quantitatively analyze the CO line SED we employ a large velocity gradient (LVG) model, in which the excitation and opacity of the CO are determined by a gas density \(n_{\text{H}_2}\), kinetic temperature \(T_{\text{kin}}\), and CO abundance per velocity gradient \((\text{CO}/\text{H}_2)\) [\(dI/dv\)]. We use an escape probability formalism with \(\beta = (1 - e^{-\gamma})/\gamma\), derived for a spherical cloud undergoing uniform collapse (Castor 1970; Goldreich & Kwan 1974). The source is assumed to contain a large number of these unresolved clouds, such that the absolute line intensities are proportional to a beam-averaged CO column density \(N_{\text{CO}}\). We increase the CO-H2 collisional rate coefficients from [C I] lines, which will be presented elsewhere (T. Nikola et al. 2009, in preparation).

3. RESULTS

3.1. LVG Model

To examine the CO excitation we assemble the lower-J line intensities from the literature and correct all measurements to a common 15″ beam. The \(^{12}\text{CO} J = 4 \rightarrow 3\) intensity is obtained from Güsten et al. (2006) and the \(J = 3 \rightarrow 2\) and lower transitions are taken from Harrison et al. (1999). The \(^{12}\text{CO} J = 6 \rightarrow 5\) map of Bayet et al. (2004) is used to correct the intensities measured here to a 15″ scale, and when necessary the intensities obtained from Harrison et al. (1999) are corrected using power-law interpolations as outlined in B03. The line intensities used in our analysis are listed in Table 1.

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![Fig. 1.—Top: Spectra of \(^{12}\text{CO} J = 6 \rightarrow 5\) and \(^{13}\text{CO} J = 6 \rightarrow 5\) (scaled by \(\times 10\)). Bottom: Spectrum of \(^{12}\text{CO} J = 7 \rightarrow 6\) and \([\text{C I}]\) \(^2P_1 \rightarrow ^2P_0\), with a rogue pixel removed near the center. The velocity scale is referenced to 12CO.

Flower (2001) by 21% to account for collisions with He (B03 and references therein), and fix the H2 ortho/para ratio at 3. All measurements have been corrected to 15″ using a methodology described in § 3.1. Intensities measured here have statistical errors listed in col. (3) and total uncertainties (30%) dominated by systematic uncertainties in the high-frequency sky transmission.

Notes.—Main beam intensities of \(^{12}\text{CO} J = 6 \rightarrow 5, J = 7 \rightarrow 6,\) and \(^{13}\text{CO} J = 6 \rightarrow 5\) from this work and lower-J intensities from Güsten et al. (2006) and Harrison et al. (1999). All measurements have been corrected to 15″ using a methodology described in § 3.1. Intensities measured here have statistical errors listed in col. (3) and total uncertainties (30%) dominated by systematic uncertainties in the high-frequency sky transmission.

3.2. High-Excitation Component

As for B03 we find that any single set of LVG model parameters capable of producing the mid-\(J\) emission underpredicts the \(J = 2 \rightarrow 1\) and \(1 \rightarrow 0\) intensities, necessitating the adoption of a two-component model. Güsten et al. (2006) find that a single component can produce the \(^{12}\text{CO}\) intensities and the \(J = 3 \rightarrow 2\) and lower transitions of \(^{13}\text{CO}\), but such a model would not account for the bright \(^{12}\text{CO} J = 6 \rightarrow 5\) emission measured here. We begin by using the \(J = 3 \rightarrow 2\) and higher transitions to constrain the high-excitation component, and then introduce a low-excitation component to account for the excess \(J = 2 \rightarrow 1\) and \(1 \rightarrow 0\) emission.

We calculate a four-dimensional grid of model CO line SEDs, varying \(n_{\text{H}_2}\), \(T_{\text{kin}}\), \(dI/dv\), and \(N_{\text{CO}}\) over a large volume of parameter space. Comparing these model calculations to the observed mid-\(J\) CO line intensities, we find solutions giving \(X_{\text{red}} \leq 1\) for values of \(dI/dv \geq 3\) km s\(^{-1}\) pc\(^{-1}\). In Figure 2 we plot the values of \(n_{\text{H}_2}\) and \(T_{\text{kin}}\) giving the best fits for velocity gradients in the range \(dI/dv = 3\)–320 km s\(^{-1}\) pc\(^{-1}\). Over the modeled range of \(dI/dv\), these values change by an order of magnitude or more, so to further restrict parameter space we must apply prior constraints to \(dI/dv\) and \(T_{\text{kin}}\).

In the LVG approximation the velocity gradient is produced by large-scale systematic motion, but for a self-gravitating cloud in virial equilibrium we can approximate \(dI/dv \approx 3.1\) km s\(^{-1}\) pc\(^{-1}\) \((n_{\text{H}_2}/10^4\) cm\(^{-3}\))\(^{0.72}\) (Goldsmith 2001). Allowing that \(dI/dv\) may be larger due to the presence of an additional stellar mass density or a high-pressure intercloud medium (B03), we set an upper limit \(\sim 10\) times larger at \(dI/dv \leq 40\) km s\(^{-1}\) pc\(^{-1}\). The value of \(T_{\text{kin}}\) is restricted by the results of Rigopoulou et

| Transition | Beam (arcsec) | \(I\) (K km s\(^{-1}\)) | \(I\) (ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\)) | \(\sigma\) (%) |
|------------|---------------|----------------------|---------------------------------|-----------|
| \(^{12}\text{CO}(6 \rightarrow 5)\) ... | 11 | 854 ± 20 | 2.89 × 10\(^{-4}\) | 30 |
| ... | 15 | 573 | 1.94 × 10\(^{-4}\) | 30 |
| ... | 10 | 694 ± 30 | 3.73 × 10\(^{-4}\) | 30 |
| ... | 15 | 418 | 2.25 × 10\(^{-4}\) | 30 |
| ... | 11 | 65 ± 5 | 1.97 × 10\(^{-4}\) | 30 |
| ... | 15 | 43 | 1.29 × 10\(^{-4}\) | 30 |
| ... | 15 | 1105 | 1.73 × 10\(^{-4}\) | 22 |
| ... | 15 | 1500 | 1.88 × 10\(^{-4}\) | 16 |
| ... | 15 | 1134 | 4.81 × 10\(^{-5}\) | 14 |
| ... | 15 | 1040 | 1.04 × 10\(^{-5}\) | 15 |
| ... | 15 | 94 | 1.29 × 10\(^{-5}\) | 20 |
| ... | 15 | 113 | 1.24 × 10\(^{-5}\) | 12 |
| ... | 15 | 117 | 4.33 × 10\(^{-5}\) | 14 |
al. (2002) who conclude that the bulk of the warm molecular gas traced by H$_2$ rotational transitions lies at $T = 195$ K. As the mid-J CO transitions arise from lower energy states than those producing the H$_2$ rotational lines we expect the mid-J CO emission to trace a cooler component and therefore require $T_{\text{kin}} \lesssim 200$ K. With these two upper limits the velocity gradient is effectively restricted to $dv/dr \approx 7-40$ km s$^{-1}$ pc$^{-1}$, with corresponding limits to $n_{H_2}$ and $T_{\text{kin}}$ (Fig. 2).

To quantify the allowed ranges of the model parameters we adopt a Bayesian formalism and calculate a posterior probability density function for each parameter (for a detailed explanation of this method see Ward et al. 2003). We assume a prior expectation of uniform probability per logarithmic interval for each parameter, subject to the upper limits on $dv/dr$ and $T_{\text{kin}}$ imposed above. We find $n_{H_2} = 10^{3.8}$–$10^{4.1}$ cm$^{-3}$, $T_{\text{kin}} = 80$–200 K, and the thermal pressure is $P/k_B = (0.8$–$1.4) \times 10^6$ cm$^{-2}$ K. The beam-averaged CO column density of this warm component is well constrained to be $N_{\text{CO}} = (1.7$–$2.2) \times 10^{16}$ cm$^{-2}$, giving an associated H$_2$ mass of $M_{H_2} = (1.2$–$1.6) \times 10^7 M_{\odot}$ in the central 180 pc. We take as our benchmark model the best-fit solution obtained by fixing $dv/dr = 20$ km s$^{-1}$ pc$^{-1}$ and plot it over the data in Figure 2.

### 3.3. Low-Excitation Component

The residual $J = 2 \rightarrow 1$ and $1 \rightarrow 0$ intensities from the benchmark model can be produced by a broad range of low-excitation components with $T_{\text{kin}} \lesssim 40$ K and $n_{H_2} \sim 10^{2.4}$–$10^{3.0}$ cm$^{-3}$, contributing a beam-averaged CO column density of $N_{\text{CO}} = (1.5$–$3.2) \times 10^{15}$ cm$^{-2}$. We therefore estimate the central 180 pc contain an H$_2$ mass of $M_{H_2} \approx 2.9 \times 10^7 M_{\odot}$, 35%–60% of which is in a warm ($T_{\text{kin}} \sim 110$ K), dense ($n_{H_2} \sim 10^4$ cm$^{-3}$) phase.

### 3.4. Comparison with Atomic Gas

Carral et al. (1994) detect 158 $\mu$m [C ii] fine-structure line emission and emission from other ionized and neutral gas tracers toward the central 45" of NGC 253. Based on a combined H i region and photodissociation region (PDR) model of the line and far-IR continuum flux, they estimate an atomic PDR mass of $M_{\text{H}} = 2.4 \times 10^6 M_{\odot}$. Scaling from the $^{12}$CO $J = 1 \rightarrow 0$ morphology (Paglione et al. 2004) we estimate half of the PDR emission arises from the central 15", giving $M_{\text{H}} \approx 1.2 \times 10^6 M_{\odot}$ in the central 180 pc, a factor of $\approx 12$ smaller than the warm molecular gas mass. PDR models generally predict comparable amounts of warm molecular and atomic components, so we conclude that the bulk of the warm molecular gas is not ultraviolet-heated gas associated with PDRs. In § 4 we explore alternative mechanisms for heating the molecular gas.

### 4. DISCUSSION: WHAT HEATS THE GAS?

#### 4.1. X-Rays

Because of their smaller cross sections, X-ray photons penetrate more deeply than ultraviolet (UV) photons into clouds and heat a larger volume of the molecular gas. In this section we consider whether an X-ray Dominated Region (XDR) can produce a warm molecular gas mass significantly in excess of the warm atomic gas mass.

Meijerink & Spaans (2005) present the thermal and chemical structure of four model XDRs, with combinations of low or high density ($n_{\text{H}} = 10^{3.0}$, $10^{3.3}$ cm$^{-3}$) and low- or high-incident X-ray flux ($F_X = 1.6, 160$ ergs s$^{-1}$ cm$^{-2}$). For each model they plot the gas abundances and temperature as a function of depth into the cloud, from which we calculate the total column densities of warm C$^+$ and CO. The 158 $\mu$m [C ii] transition used to trace the warm atomic component arises from a state 91 K above ground, so we include only C$^+$ warmer than 91 K. We include all CO warmer than 80 K, the minimum temperature allowed by our CO excitation analysis. The large observed ratio of $N_{\text{CO}}/N_{\text{C}}^+ \approx 1.7$ (corresponding to $M_{\text{H}}/M_{\text{C}}^+ \approx 12$ as discussed in § 3.4) can only be produced by the high-density ($n_{\text{H}} = 10^{3.5}$ cm$^{-3}$), high-flux ($F_X = 160$ ergs s$^{-1}$ cm$^{-2}$) model.

The model XDRs use densities which are an order of magnitude larger or smaller than the value of $n_{\text{H}} = 2 n_{H_2} \sim 10^{4.3}$ cm$^{-3}$ indicated by our LVG analysis. Interpolating between the high-density, high-flux model and the lower density models, we estimate an XDR with $n_{\text{H}} = 10^{4.4}$ cm$^{-3}$ will match the observed $N_{\text{CO}}/N_{\text{C}}^+$ ratio only if $F_X \geq 10$ ergs s$^{-1}$ cm$^{-2}$. However, such an XDR will produce an [O i] $63 \mu$m/[C ii] 158 $\mu$m ratio more than $\approx 20$ times larger than observed (Carral et al. 1994; Meijerink et al. 2007), and consequently we rule out an XDR as a potential source of the mid-J CO emission.

#### 4.2. Cosmic Rays

It is generally accepted that low-energy cosmic rays control the thermal and chemical balance in the UV-shielded inner cores of Galactic molecular clouds (Goldsmith & Langer 1978). B03 estimates that the high supernovae rate in the nucleus of NGC 253 results in a cosmic-ray ionization rate 750 times higher than in the Galactic plane and that these cosmic rays...
deposit \((5-18) \times 10^{-25}\) \text{ ergs s}^{-1} \text{ per H}_2 \text{ molecule in the molecular gas. By summing the integrated intensities predicted by our benchmark LVG model over all rotational transitions, we estimate a warm molecular gas mass of } M_{\text{shock}} \approx \begin{bmatrix} 1.4 \times 10^8 M_\odot \end{bmatrix} \text{ produces a CO luminosity of } L_{\text{CO}} \approx \begin{bmatrix} 1.6 \times 10^6 L_\odot \end{bmatrix} \text{ corresponding to a specific cooling rate of } \begin{bmatrix} 6.9 \times 10^{-25} \text{ ergs s}^{-1} \text{ per H}_2 \text{ molecule. As this cooling rate matches the heating rate estimated by B03 we suggest an elevated cosmic-ray density resulting from the starburst may provide the origin of the warm molecular gas.}

4.3. Shocks

The molecular gas in the center of NGC 253 shows evidence of shock-driven chemistry, including the large gas-phase abundance of silicon (Carral et al. 1994; García-Burillo et al. 2000), and the general chemical similarity to shock-dominated molecular clouds in the Galactic center (Martin et al. 2006). In this section we consider whether the mid-J CO emission may arise from shock-heated gas.

The emission from C-shocks is modeled by Draine et al. (1983) and Draine & Roberge (1984). In addition to the rotational transitions of CO, the dominant coolants are the H2 rovibrational transitions and the 63 \text{ m } \mu \text{ transitions of CO, the dominant coolants are the H2 rovibrational (1983) and Draine & Roberge (1984). In addition to the rotational}

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