

TEMPERATURE AND DENSITY GRADIENTS ACROSS THE NUCLEUS OF M82

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ABSTRACT

This Letter presents ^{12}CO $J = 3-2$, ^{13}CO $J = 3-2$, C^{18}O $J = 3-2$, and ^{13}CO $J = 2-1$ spectra of the irregular starburst galaxy M82 taken with the 15 m James Clerk Maxwell Telescope. All maps exhibit a double-peaked morphology, despite evidence that the higher J transitions are optically thick. This morphology suggests that the double-peaked structure is not the result of an edge-on torus of molecular gas, as is commonly assumed. We observe line ratio gradients that can best be explained by a temperature gradient increasing from northeast to southwest in conjunction with a density gradient that increases in the opposite sense. These gradients may have been caused by the interaction with M81, resulting in increased star formation that both heats and depletes the molecular gas in the southwest lobe of M82.

Subject headings: galaxies: individual (M82) — galaxies: irregular — galaxies: ISM — ISM: molecules — Local Group

1. INTRODUCTION

M82 (NGC 3034, Arp 337) is considered the prototypical starburst galaxy. Its close proximity ($D = 3.25$ Mpc; Tammann & Sandage 1968) and strong CO lines (Rickard et al. 1975) make it an excellent galaxy in which to study the effects of a burst of star formation on molecular gas properties. Its edge-on orientation makes essential the use of optically thin molecular gas tracers for probing the physical conditions in the interstellar medium. Interferometric maps (e.g., Shen & Lo 1995; Neininger et al. 1998) show that M82 contains three bright lobes: two main lobes on the outer edges, which are thought to be a torus of molecular gas seen edge-on (e.g., Tilanus et al. 1991), and a central peak, which may be housing an active galactic nucleus (Muxlow et al. 1994; Sequist, Frayer, & Frail 1997). Early CO studies showed that M82 had an unusually large ^{12}CO $J = 2-1/J = 1-0$ line ratio ($\gtrsim 2$; Knapp et al. 1980; Sutton, Masson, & Phillips 1983), which suggested that the ^{12}CO gas in M82 is optically thin. As calibration techniques and telescope surface quality improved, the value for the ^{12}CO $J = 2-1/J = 1-0$ line ratio has decreased to ~ 1 (Tilanus et al. 1991; Wild et al. 1992), which suggests that ^{12}CO is likely optically thick. A high optical depth leads to some problems in the interpretation of the double lobes as a molecular torus. Neininger et al. (1998) point out that if the gas were optically thin, a torus seen from the edge would have a double-peaked appearance, while if the torus were optically thick, we should see a elongated, barlike structure.

Mapping a galaxy in many transitions will help increase our understanding of the molecular gas dynamics, since different transitions and molecules do not necessarily trace the same gas (Petitpas & Wilson 1998b; Kohno, Kawabe, & Vila-Vilaró 1999). While M82 has been painstakingly mapped and studied by many authors in the lower J transitions of CO and its isotopomers (see references above), improvements in receiver sensitivity and telescope surface quality have made fully sampled maps of the higher J transitions of rarer CO isotopes more tractable. This Letter presents first results from ^{12}CO , ^{13}CO , C^{18}O $J = 3-2$, and ^{13}CO $J = 2-1$ maps of M82. In § 2 we describe the observations and discuss the appearance of the spectra in comparison to each other and previously published

data. In § 3 we use integrated intensity line ratios to derive the physical conditions inside the nucleus of M82 and discuss the results and possible causes for the observed gradients.

2. OBSERVATIONS AND DATA REDUCTION

One of the difficulties in the interpretation of line ratios is that the different lines are often measured with different telescopes. This method introduces calibration uncertainties (see, for example, Fig. 6 of Wild et al. 1992) that can be reduced if all the data are taken with the same telescope (which is often impossible, given the large variation in frequency between some transitions).

A variety of CO $J = 3-2$ observations of M82 were taken using the James Clerk Maxwell Telescope (JCMT) over the period of 1996 April 5–10. The ^{12}CO $J = 3-2$ map covers an area of $120'' \times 100''$, the ^{13}CO $J = 3-2$ map covers $56'' \times 35''$, and the C^{18}O $J = 3-2$ map covers a $34''$ strip along the bar's major axis. We also include ^{12}CO and ^{13}CO $J = 2-1$ data taken during CANSERV at the JCMT over 1993 April 22–25. The data were reduced using the data reduction package SPECX. The raw data had a linear baseline removed, and then the $J = 3-2$ data were binned to 12.5 MHz (10.8 km s^{-1}) and the $J = 2-1$ data to 5 MHz (6.7 km s^{-1}). Since the CO $J = 2-1$ data have a different beam size and grid spacing than the CO $J = 3-2$ data, it was necessary to interpolate and convolve the spectra before measuring the integrated intensity line ratios. The data were exported to the data reduction package COMB, and the CO $J = 3-2$ data were convolved to the same beam size and interpolated to the same location as the nearest CO $J = 2-1$ spectra.

The calibration was monitored by frequently observing both planets and spectral line calibrators. The spectral line calibrators for the CO data had intensities that were within $\sim 15\%$ of the published values. We therefore adopt the published values for η_{MB} of 0.58 for the CO $J = 3-2$ data and 0.67 for the ^{12}CO $J = 2-1$ data. Pointing was checked frequently and was determined to be accurate to within $2''$ rms.

The individual ^{12}CO $J = 3-2$, ^{13}CO $J = 3-2$, C^{18}O $J = 3-2$, ^{12}CO $J = 2-1$, and ^{13}CO $J = 2-1$ spectra for the three bright regions of M82 are shown in Figure 1. The individual

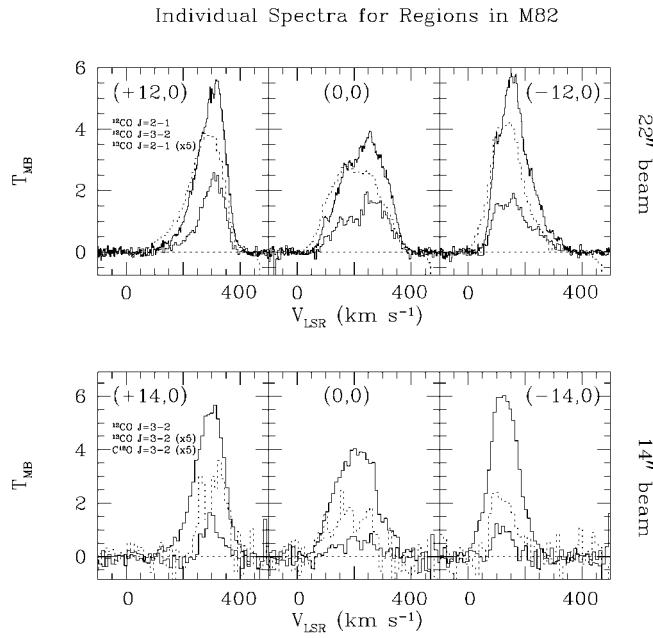


FIG. 1.—Individual spectra for the starburst galaxy M82. The transitions are labeled in the same vertical order as they appear in the plots. The (0, 0) position is centered on $\alpha = 09^{\circ}51'43\overset{.}{0}\text{0}$, $\delta = 69^{\circ}55'00\overset{.}{0}\text{0}$ (B1950.0). The orientation is such that north corresponds to an angle of 70° from the positive x -axis, and the bar runs horizontally. The temperature scale is main-beam temperature. The top panel shows the spectra taken with (or convolved to) a $22''$ beam, while the bottom panel shows data taken with a $14''$ beam.

spectra for M82 appear asymmetric on either side of the center, indicating rotation. The line profiles appear similar for each transition, which indicates that, at least on large scales, the emission is coming from comoving material. There are indications of double-peaked line profiles at the (0, 0) position in the $J = 2-1$ spectra. Since we do not see this structure as strongly in the $J = 3-2$ spectra, it is likely the result of the larger beam overlapping both the northeast and southwest peaks simultaneously.

3. PHYSICAL CONDITIONS FROM LINE RATIOS

It is well known that the filling factor of molecular clouds in a galaxy is often low. Thus, integrated intensities are generally not a good measure of the physical conditions of individual molecular clouds because the signal is diluted by the large radio telescope beams, which also cover much empty space. We must therefore use integrated intensity line ratios to determine the physical conditions of individual clouds. Using the ratio of two integrated intensities will help cancel out the effects of beam dilution, assuming that similar regions of space are responsible for the emission at both frequencies. The physical conditions recovered from the analysis of line ratios are the average conditions for all clouds within the beam.

The differing morphology in the ^{13}CO and ^{12}CO $J = 3-2$ lines results in a gradient of the $^{12}\text{CO}/^{13}\text{CO}$ $J = 3-2$ line ratios, increasing from east to west (Fig. 2). If both lines are optically thin, this observation indicates a $^{13}\text{CO}/^{12}\text{CO}$ abundance gradient across the disk of M82. This same “abundance”-type gradient is not visible in the lower J transitions (see $^{12}\text{CO}/^{13}\text{CO}$ $J = 1-0$ and $J = 2-1$ ratios; Neininger et al. 1998; Loiseau et al. 1990), which suggests that the ^{12}CO emission is not optically thin and the gradient may be the result of a variation in optical

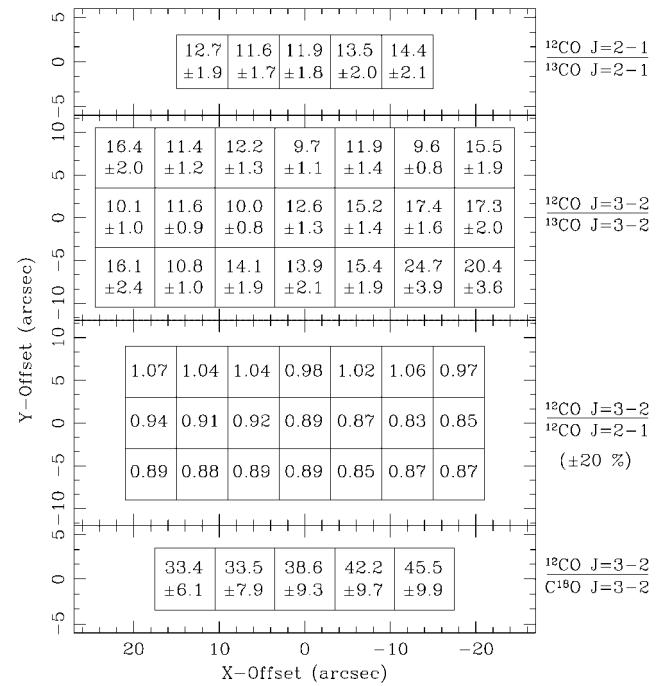


FIG. 2.—Integrated intensity line ratios for $^{12}\text{CO}/^{13}\text{CO}$ $J = 2-1$, $^{12}\text{CO}/^{13}\text{CO}$ $J = 3-2$, ^{12}CO $J = 3-2/J = 2-1$, and $^{12}\text{CO}/\text{C}^{18}\text{O}$ $J = 3-2$ (from top to bottom, respectively). The ratios are in main-beam temperature scale (T_{MB}). The uncertainties are based on the rms noise in the data, except for the ^{12}CO $J = 3-2/J = 2-1$ ratio, which is given as 20% to reflect the calibration uncertainties. The $J = 3-2$ line ratios use data taken with a $14''$ beam size; the $J = 2-1$ line ratio uses $22''$ resolution data. The ^{12}CO $J = 3-2$ data were convolved to a $22''$ beam to create the ^{12}CO $J = 3-2/J = 2-1$ line ratios.

depth. Since optical depth is a function of density and temperature, we have performed a large velocity gradient (LVG) analysis using a code written by L. Mundy and implemented as part of the MIRIAD data reduction package. A single-component model provided a very nice fit to the observed line ratios. We kept the C^{18}O abundance as a free parameter, so a survey of parameter space was performed using $T_{\text{kin}} = 50 \pm 20$ K (Wild et al. 1992), $[^{12}\text{CO}]/[^{13}\text{CO}] = 50 \pm 20$ (Tilanus et al. 1991), $n(\text{H}_2)$ from 10 to 10^6 cm^{-3} , and $N(\text{CO})/dv$ from 10^{15} to $10^{20} \text{ cm}^{-2} (\text{km s}^{-1})^{-1}$ (see Petitpas & Wilson 1998a for more details). The $\pm 1\sigma$ error bars for the line ratios shown in Figure 2 were entered into the program, and the solutions are shown in Table 1. The ^{12}CO $J = 2-1/J = 1-0$ ratios from Tilanus et al. (1991) also overlap our solutions.

In the simplest scenario, the observed line ratio gradients can be explained by varying either temperature or density across the galaxy while holding the other variable constant. Our analysis suggests that either the density varies from 1.6×10^4 to $0.6 \times 10^4 \text{ cm}^{-2}$ (for $T_{\text{kin}} = 50$ K) or the temperature varies from 70 to 30 K [for $n(\text{H}_2) = 10^4 \text{ cm}^{-3}$] from east to west. Of course, the gradients can also be produced by a combination of varying T and n , which suggests that we need to include observations at other frequencies to constrain the models.

A similar line ratio gradient was seen in $\text{HCO}^+ J = 4-3/J = 1-0$ by Seaquist, Frayer, & Bell (1998), but since their data combined single-dish and interferometry data, they dismissed the gradient, attributing it to an abundance of diffuse emission on the eastern side of M82, which would cause the HCO^+ emission to be underestimated. However, our model fits show a higher density and/or temperature in the northeast lobe, which could produce an increased $\text{HCO}^+ J = 4-3/J = 1-0$ ratio.

TABLE 1
M82 LVG SOLUTIONS

T_{kin} (K)	$^{12}\text{CO}/^{13}\text{CO}$ Abundance Ratio	Fit to the $^{12}\text{CO}/^{18}\text{CO}$ Abundance Ratio	$\log N(\text{CO})/dv$	$\log n(\text{H}_2)$	$\tau_{J=1-0}$	$\tau_{J=3-2}$	Preferred Solution?
Northeast Lobe (+12, 0)							
30	30	100	16.5	4.4	0.5	3	Yes
	50	100	16.6	4.4	1.1	5	Yes
	70	200	17.0	4.5	3.5	15	Yes
50	30	100	16.8	4.2	0.4	4	No
	50	150	17.0	4.2	1.0	7	No
	70	200	17.2	4.2	2.1	12	No
70	30	100	16.7	4.0	0.1	3	No
	50	150–200	17.0	4.0	0.5	5	No
	70	200–250	17.4	4.0	1.2	9	No
Southwest Lobe (-12, 0)							
30	30	75	16.3	4.0	0.6	3	No
	50	100–150	16.6	4.1	1.3	6	No
	70	200	16.7	4.1	1.2	6	No
50	30	75	16.4	3.7	0.2	3	No
	50	150	16.8	3.8	0.6	5	No
	70	200	17.0	3.8	1.2	8	No
70	30	75	16.4	3.6	0.1	3	Yes
	50	100–150	16.8	3.7	0.4	5	Yes
	70	200	17.0	3.7	0.9	8	Yes

NOTE.—This table shows all the possible solutions for the JCMT line ratios for $T_{\text{kin}} = 50 \pm 20$ and $[^{12}\text{CO}]/[^{13}\text{CO}] = 50 \pm 20$. The first column is the kinetic temperature, the second column is the $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio, and the third column is the fit to the $^{12}\text{CO}/^{18}\text{O}$ abundance ratio. The fourth and fifth columns are the CO column density (per km s⁻¹) and H₂ density required to produce the observed line ratios, while the sixth and seventh columns are the optical depth for the $^{12}\text{CO} J = 1-0$ and $^{12}\text{CO} J = 3-2$ transitions, respectively. The last column indicates the solutions that are preferred when considering data at other frequencies (see text).

Previous ^{12}CO and $^{13}\text{CO} J = 1-0$ interferometric studies by Kikumoto et al. (1998) find $^{12}\text{CO}/^{13}\text{CO} J = 1-0$ ratios that increase across M82, but in the opposite direction from our $J = 3-2$ ratios. This result helps rule out the possibility that the observed gradients are the result of a ^{13}CO and C¹⁸O abundance gradient across M82. The $J = 1-0$ line ratio gradients are likely the result of the higher temperatures and/or densities in the northeast lobe of M82, which bump the CO into the higher J transitions, leaving the lower J levels less populated.

We can use the 850 μm continuum maps of M82 (Alton, Davies, & Bianchi 1999) to remove the degeneracy between density and temperature in our models. Since the southwest lobe is brighter in the 850 μm continuum maps, which trace the product of the temperature and the column density, we can conclude that the column density or temperature (or both) is higher in the southwest lobe. In this scenario, the HCO⁺ maps of Seaquist et al. (1998) would require that density be higher in the northeast. The pair of LVG solutions that best satisfies the combined CO, HCO⁺, and continuum data are indicated in Table 1. Utilizing these additional data sets, we therefore conclude that the observed line ratios are the result of a temperature gradient that increases from northeast to southwest in conjunction with a density gradient that increases from southwest to northeast.

One possible reason for this density and temperature gradient may be interaction with the nearby galaxy M81. Gravitational interaction may be triggering vigorous star formation in the southwest lobe, which could be heating the gas (increasing T) at the same time that it is being consumed (decreasing the average density by turning the densest regions into stars). While previous galaxy interaction simulations do not show any indication of density gradients across the smaller galaxy, it is unlikely that the current simulations would be able to detect a factor of 3 difference in the mean density of molecular clouds across the galaxy.

There is some dispute over the nature of the double-peaked

structure seen in M82. Most studies suggest that it is the result of a molecular torus seen edge-on. This would only be the case if the molecular gas in the clouds were optically thin (Neininger et al. 1998) or there were not enough molecular clouds in the telescope beam to “shadow” the more distant clouds. Our LVG analysis indicates that the $^{12}\text{CO} J = 1-0$ transition is on the border between optically thin and optically thick ($\tau_{J=1-0} \sim 0.1-3.5$). However, the $J = 2-1$ and $J = 3-2$ maps also indicate a double-peaked structure, even though these transitions are likely optically thick (Table 1). This result can only be consistent with the torus model if the filling factor of the optically thick clouds within the beam is low enough that shadowing of one cloud by another is not a problem. We can estimate the filling factor by comparing the predicted and observed line temperatures. The LVG models predict temperatures of 19 K for $^{12}\text{CO} J = 2-1$, while our data show temperatures of ~ 6 K. In addition, the high-resolution CO maps of Neininger et al. (1998) suggest that M82 is only $\sim 10''$ thick and thus the filling factor of the CO emission is $\sim 60\%$ of the 22'' JCMT beam. This filling factor is high enough that cloud shadowing may be important in this region. If cloud shadowing plays a large role, the double-peaked structure in M82 could not be explained as the result of an edge-on torus of molecular gas. Instead, it could be produced by the accumulation of molecular gas at the inner Lindblad resonance radius as it flows inward along the bar (e.g., Kenney et al. 1992). There is evidence for these double peaks (on similar size scales) in nearly face-on barred galaxies (Kenney et al. 1992; Petipas & Wilson 1998b), where we would not expect them to be caused by the torus of gas, since the torus would have to be out of the plane of the galaxy.

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