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CO (2-1) IN IC 342

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ABSTRACT We present aperture synthesis maps of the CO J=2–1 emission in the central region of the spiral galaxy IC 342. The 4″ resolution maps reveal emission that is a factor of two brighter than the CO (1–0) emission mapped at the same resolution. Since the CO (2–1) emission is likely to be optically thick, the high ratio is probably due to the fact that the two transitions sample different cloud layers in externally heated clouds. The high signal to noise of the maps indicates that CO (2–1) will be a powerful tool in the study of gas in galaxies.

INTRODUCTION

Aperture synthesis observations of the J=2–1 transition of CO at 1.3 mm are now possible with the Owens Valley Millimeter Interferometer. Interferometry is particularly important for observations of CO in external galaxies, where high spatial resolution is crucial for understanding the distribution of molecular gas on sizescales typical of giant molecular clouds. The move to CO (2–1) is an important development. In addition to gain of a factor of two in resolution for a given baseline, other advantages of the CO(2–1) transition over the CO(1–0) transition include the possibility of increased intensity for optically thin lines and a $\sqrt{2}$ improvement in sensitivity for a given velocity resolution. CO (2–1) may prove to be an extremely useful tracer of molecular gas in galaxies, potentially even more powerful than CO (1–0).

IC 342 is an excellent candidate for the first studies of CO (2–1). An Scd galaxy at a distance of 1.8 Mpc (McCall 1989), it is the closest large spiral with significant amounts of molecular gas. There is a moderately large starforming complex in the nucleus (Becklin et al. 1980; Turner & Ho 1983). CO (1–0) observations show that the molecular gas, which may constitute as much as 50% of the total mass in the inner hundred pc (Turner & Hurt 1992), is distributed in a barlike structure of $\sim$ 500 pc extent (Lo et al. 1984; Levine, Turner, & Hurt 1993, this volume) in the form of two very open spiral "arms" (Ishizuki et al. 1990). Turner & Hurt (1992) suggest that these arms, which lie to the inner, convex side of Hα arms (J. S. Young 1992, private communication), and the strong radial motions observed in the gas, are the response to a spiral density wave that extends to within 50 pc of the nucleus.

The goals of this study are the comparison of CO (2–1) morphology, brightness, and kinematics in IC 342 to that of CO (1–0). We are interested not only in what this comparison will tell us about the properties of the molecular gas in the nucleus of IC342, but also about the comparative value of the CO (2–1) line as a tracer of molecular gas in galaxies.

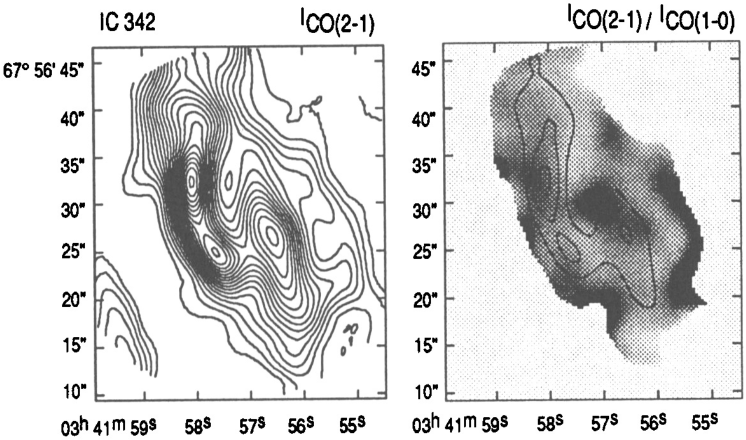

FIGURE I a) CO (2–1) integrated intensity, $I_{CO(2-1)}$, in IC 342. Contour levels are in units of 40 Jy bm^{-1} km s^{-1}, or 61 K km s^{-1}. The peak is 1300 K km s^{-1}. b) Ratio of CO (2–1) integrated intensity to CO (1–0) integrated intensity. The greyscale range is 1 to 2.7, with darker shades representing higher values. For reference, the 400, 600, and 800 Jy bm^{-1} km s^{-1} contours of $I_{CO(2-1)}$ are plotted.

OBSERVATIONS

Observations of IC 342 in the CO (2-1) line at 230.538 GHz (1.3mm) were made with the Owens Valley Millimeter Interferometer on 1990 December 26 and 1991 January 24. The interferometer consisted of three 10.4 m antennas with cooled SIS receivers as described in Woody et al. (1989) and Padin et al. (1991). Two twelve hour tracks of the array were used to synthesize a 4.1″ x 3.7″ beam. System temperatures ranged from 800-900 K (SSB). Instrumental phase was calibrated through observations of the point source 0224+671. The absolute flux calibration is based on observations of the planet Uranus and is good to ~ 30%. The maps were made using 5 MHz filters, for a velocity resolution of 6.5 km s^{-1}. The maps were made and CLEANed using the NRAO AIPS package. Correction has been made for the primary beam response of the antennas (~ 34″ FWHM, at 230 GHz). The sensitivity of the maps, 0.2 mJy/beam, or 0.3 K, is limited by our ability to sufficiently CLEAN the extended emission. The dynamic range in the channel with the strongest emission is close to 100:1.

RESULTS

The integrated intensity map of CO (2–1) in IC 342 appears in Figure I a. The general morphology of the CO (2–1) emitting region is very similar to that of the CO (1–0), with two very open arms of emission coming into the nucleus (Lo et al. 1984; Ishizuki et al. 1990; Turner & Hurt 1991). The most intense emission falls in three major peaks that are within 50 pc of the dynamical center, located at $03^h\ 41^m\ 57.6^s$, $67^\circ\ 56'\ 28''$ (Turner & Hurt 1992). The kinematics of the CO (2–1) are also similar to that of the CO (1–0), with an apparent "solid body" rotation region within the inner 100 pc changing to a strong radial flow along the arms in the outer regions (Lo et al. 1984; Ishizuki et al. 1990).

Intensities in the individual channel maps range from 2 K (7σ) to 24 K. When corrected for the Rayleigh-Jeans approximation, these correspond to brightness temperatures of $T_b = 6$–30 K. These values are quite high given that the excitation temperature of the gas is unlikely to be higher than the observed dust temperature of 47 K (Rickard & Harvey 1984) and beam dilution is likely to be important over the 35 pc extent of the beam. These CO(2–1) peak temperatures are also significantly higher than those seen in CO(1–0).

The ratio of I_{2-1}/I_{1-0} is on average about 1.7 across the nucleus with a total range of 1–2.7. These values, which are significantly higher than unity, might appear to indicate that the gas is optically thin. However, there are several independent indications that the gas is not thin, but optically thick. First, the brightness temperature of the emission is quite high, in spite of beam dilution. This requires at least moderate optical depths. Second, the H_2 column densities indicated by ^{13}CO emission are high, $N_{H_2} \sim 10^{22} - 10^{23}\,\mathrm{cm}^{-2}$ (Turner & Hurt 1992), which is difficult to reconcile with low optical depths. And finally, for an excitation temperature of 47K, equal to the dust temperature (Rickard & Harvey 1984), we obtain from the observed 2–1 intensities a range of column densities of $N_{H2} = 4 \times 10^{20} - 8 \times 10^{21}$ by assuming that the CO (2–1) line is optically thin. These column densities, a measure of the column density to optical depth unity, are an order of magnitude lower than those obtained from the ^{13}CO. This result also suggests that the CO (2–1) samples only the outermost layers of the clouds.

The apparent contradiction between the high I_{2-1}/I_{1-0} values and the evidence that the CO (2–1) is optically thick is resolved easily if the CO (2–1) arises in warmer gas than does the CO (1–0). Since CO (2–1) is optically thicker than CO (1–0), it will tend to trace a comparatively thin outer layer of the cloud. The CO (2–1) intensity will be enhanced relative to the CO (1–0) if these outer layers are warmer than the inner portion of the cloud. This might be expected for clouds heated on the outside by uv photons. We feel that this explanation for the enhanced CO (2–1) intensities is more likely than that of optically thin gas.

The spatial variations in I_{2-1}/I_{1-0} evident in Figure 1b give further information on the CO excitation in these clouds. Aside from enhanced values near the edges of the map due to low signal to noise, there are two peaks in this ratio that appear to be significant. Both peaks appear to be consistent with the picture of externally heated clouds. The first is the peak value of I_{2-1}/I_{1-0} of 2.7, which is located at the position of the radio continuum and 10μ m source (C. Telesco 1992, private communication), at $03^h\ 41^m\ 56.8^s$, $67^\circ\ 56'\ 28''$. Near this large HII region, high uv fluxes and particularly warm gas might be expected. The high column densities at this location indicate high optical depths, which would be required for the CO (2–1) and CO (1–0) to reflect different temperatures within the clouds. It is also possible that the other I_{2-1}/I_{1-0} peak, located just to the east of the northern CO peak, can be explained in this manner. Although the radio continuum and 10μm emission are weak in this region, there is strong Hα emission to the eastern side of the northern CO arm (J. Young 1992; see also Turner & Hurt 1992). The star formation on the outer edge of the northern spiral arm may therefore preferentially warm the gas on the eastern side of the arm, causing a relative enhancement of the CO (2–1) emission.

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REFERENCES

Becklin, E. E., Gatley, I., Matthews, K., Neugebauer, G., Sellgren, K., Werner, M. W., & Wynn-Williams, C. G. 1980, ApJ, 236, 441

Ishizuki, S., Kawabe, R., Ishiguro, M., Okumura, S. K., Morita, K.-I., Chikada, Y., & Kasuga, T. 1990, Nature, 344, 224

Lo, K. Y., et al. 1984, ApJ, 282, L59

McCall, M. L. 1989, AJ, 97, 1341

Padin, S., Scott, S. L., Woody, D. P., Scoville, N. Z., Seling, T. V., Finch, R. P., Ciovanine, C. J., & Lawrence, R. P. 1991, PASP, 103, 461

Turner, J. L. & Ho, P. T. P. 1983, ApJ, 268, L79

Turner, J. L., & Hurt, R. L. 1992, ApJ, 384, 72

Woody, D. P., Scott, S. L., Scoville, N. Z., Mundy, L. G., Sargent, A. I., Padin, S., Tinney, C. G., & Wilson, C. D. 1989, ApJ, 337, L41

Wright, M. C. H., Ishizuki, S., Turner, J. L., Ho, P. T. P., & Lo, K. Y. 1992, ApJ, in press

DISCUSSION

Z. Wang When you talked about the externally heated molecular cloud, do you mean heating by HII regions?

J. Turner Yes, that's what we are thinking about, but shock heating in spiral density waves is also possible.

M. Cameron Our map of the ^{12}CO J=2-1 emission from the disk of Ceutaurus A reveals a morphology very similar to the CO J=1-0 map. The 2-1/1-0 ratio in the disk is ~ unity, suggesting the presence of extensive heating sources throughout the dust lane. How extended are the heating sources in IC342?

J. Turner There are star forming regions tracing the outer edge of the nuclear spiral, as indicated by the Hα image (see Turner and Hurt, 1991, ApJ, 389). The large star forming region traced by radio continuum is located at the I_{2-1}/I_{1-0} peak.

K.Y. Lo It is very important to determine from your 2 μm observations of IC342 whether there is any deviation from axisymmetry of the stellar distribution. A very small amount is sufficient to cause substantial response by the gas.

J. Turner There is no evidence for non-axisymmetry in the stellar distribution. It is likely that the self-gravity of the gas is more important than any small deviation from axisymmetry is this case anyway.

J. Kenney Can you clearly distinguish between a bar and a spiral density wave in the center of IC342? A bar can also produce curved dust lanes and radial streaming motions. The basic difference, of course, is the shape of the gravitational potential.

J. Turner The data are consistent with a density wave. Moreover, there is no evidence in a stellar bar in IC342. The high molecular gas fraction suggests that the density wave may be predominantly gaseous and not stellar.

R. Genzel Modeling of observations of various CO isotopes in rotational transition up to J=6-5 (Hanis et al.1991, Eckert et al.1990) result in a kinetic temperature of about 24k, in agreement with your results. External heating of clouds can in fact produced 2-1/1-0 CO ratios greater than 1, according to recent radiative transfer models of externally heated clouds by Stutzki and collaborators in Cologne.

J. Turner Yes, it is important to verify these temperatures with an interferometer, where matching beams eliminate the beam dilution uncertainty.

R. Genzel If there is no central bar wouldn't one have to conclude that the central disk of IC342 has a different inclination angle from the larger scale?

J. Turner The lack of axisymmetry could be due to a gaseous density wave and also there is evidence that regions of high molecular mass fraction can give very open spiral arms. So there is no need to conclude that the central inclination is different although it may be.

M. Hayashi If we make a radiative transfer calculation, we usually get similar critical densities for both the J=2-1 and J=1-0 transitions, which may suggest that the effective emitting area for J=2-1 and J=1-0 emissions are similar. How do you account for your high J=2-1 to J=1-0 ratio if both transitions arise from emitting regions with similar size?

J. Turner The high I_{2-1}/I_{1-0} ratio may be due to strong temperature gradients within the molecular clouds. These especially thick transitions are not very useful as probes of cloud conditions - we are interested in this ratio mostly because we want to know how reliable a tracer of gas morphology and kinematics CO(2-1) really is. The ^{13}CO(2-1) and (1-0) lines well give much better information on the physical conditions in these clouds.