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DETECTION OF CO EMISSION FROM MASSIVE MOLECULAR CLOUDS IN THE INNER DISK OF M31

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ABSTRACT

Faint emission in the CO(1–0) and CO(2–1) spectral lines at millimeter wavelengths has been discovered from dark dust clouds in the inner disk of M31. These dust clouds are located in regions of the galaxy where there is little evidence of star-forming activity. The CO emission from these clouds is resolved, and comes from roughly the same area covered by the dust clouds (typically 200 × 600 pc). The line profile widths and cloud sizes imply cloud masses of a few $\times 10^7$ $M_\odot$, typical for giant molecular clouds (GMCs) in the Galaxy. However, the observed surface brightnesses are only a few tenths of a Kelvin, and the typical CO(1–0) luminosities are a factor of ~ 10 smaller than those of Galactic GMCs of the same size and velocity line width. The cloud temperatures are uncertain; the CO(2–1)/CO(1–0) line ratios are very low, suggesting subthermal excitation, and precluding use of this ratio alone to determine the kinetic temperature. However, there are indications that the kinetic temperatures are significantly lower than the values of 10–30 K typical for Galactic GMCs, and may be close to the 2.7 K cosmic background.

Subject headings: galaxies: individual (M31) — galaxies: ISM — ISM: molecules — radio lines: galaxies

1. INTRODUCTION

It has been known since the first major census of H II regions in M31 (Baade & Arp 1964) that this galaxy shows extensive star-forming activity in a broad ring from roughly 8 to 11 kpc radius.[1] It is this ring that we also find the brightest H I (e.g., Brinks & Shane 1984) and CO (Koper et al. 1991) spectral line emission, as well as the radio (e.g., Beck & Gräve 1982) and infrared (Walterbos & Schwering 1987) continuum emission. Inside this ring the tracers of recent massive star formation virtually disappear. The low-resolution CO(1–0) survey with the CfA dish (Koper et al. 1991) shows little or no emission inside the ring. Higher resolution CO(1–0) surveys of Stark (1979) and Sandqvist, Elfhag, & Lindblad (1989) found nothing in the inner disk region. Unfortunately Stark started observing along the minor axis only at 4′ from the center on the NW side (no signal) and at 5′ on the SW side (detection), while Sandqvist et al. resumed their minor-axis observations only at 7′ from the center. Brinks & Shane (1984) found only weak and spotty H I emission from the disk inside the ring at 8–11 kpc. However, the straightforward conclusion that there is little gas inside this ring is unlikely, since dust can be traced all over the visible disk of M31 (Baade 1958; Walterbos & Kennicutt 1988), and dust clouds have been cataloged there by the hundreds (Hodge 1980b).

Except possibly near the nucleus of the galaxy, any molecular gas associated with the dust clouds inside the star-forming ring in M31 is likely to be cold. In the absence of nearby active star-formation regions, the remaining significant heat source is most likely to be low-energy cosmic-ray primaries, mostly protons (e.g., Goldsmith & Langer 1978; Black 1987). There is little nonthermal radio continuum inside the star-forming ring, suggesting that either the cosmic-ray density is low, or the magnetic field is weak, or both. The filamentary structure of many dust patches suggests the existence of a magnetic field; it is therefore likely that the density of cosmic-ray electrons, and therefore also of low-energy protons, is low. The molecular gas would then be quite cold.

Support for this view of the physical state of the molecular clouds inside the star-forming ring of M31 has recently been provided by the discovery of a correlation between the surface brightnesses of CO(1–0) and of the centimeter nonthermal radio continuum emission in the disks of normal galaxies. This relation, first established clearly by Adler, Allen, & Lo (1991) with a sample of eight nearby galaxies, has also been extended recently to include the Galaxy (Allen 1992). The explanation offered by those authors is that both of these apparently disparate emissions owe their existence quite directly to cosmic rays; the low- and intermediate-energy primary component (mainly protons) is responsible for heating the interstellar medium and thereby exciting the CO(1–0) emission, and the high-energy electron component provides the nonthermal radio emission. This picture implies that the CO brightness is more an indicator of *temperature* of the ISM than it is an indicator of the column density of molecular hydrogen (H_2) and, furthermore, that on the scale of 1–3 kpc, these temperatures vary only slowly throughout a given galaxy. In regions of faint radio continuum emission, one may therefore expect to find faint CO emission.

2. OBSERVATIONS

We have observed several dark clouds in M31 with 30 m IRAM millimeter radio telescope at Pico Veleta in Spain. We report here the detection of CO(1–0) and CO(2–1) emission from two of these clouds, D268 (2′.1 × 1′.2, in Baade's "S2" arm) and D478 (6′.5 × 1′.1, in "N2"). The designations and angular sizes are from the tabulation by Hodge (1980b). Both

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[1] We adopt the conventional scale of 1′ = 200 pc at the distance of M31.

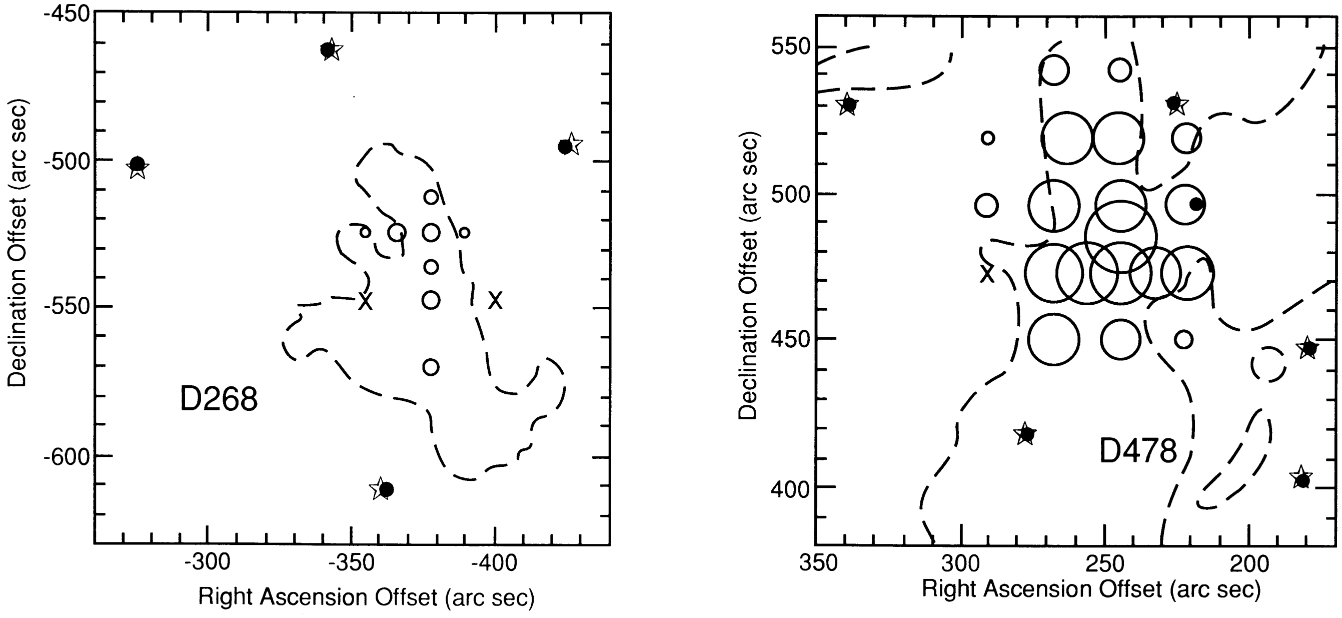

FIG. 1*a*

FIG. 1*b*

FIG. 1.—(*a*) Sketch of the M31 dark cloud D268. The diameters of the circles are proportional to $I_{\rm CO}$ (1–0) at each sampled position. The cloud boundaries are taken from Chart 6 in Hodge (1980a). The crosses indicate nondetections, and the stars are positions of optical objects in the field as determined in the GSC-I coordinate system. The coordinate axes are offsets from the (1950) adopted center of M31 at $\alpha = 00^{\rm h}40^{\rm m}0^{\rm s}.3$, $\delta = +40°59'43''.0$. (*b*) Sketch of D478; the circle diameters have the same scale as for D268. Cloud boundaries are from Chart 2 in Hodge (1980a); other symbols are the same as for Fig. 1*a*.

clouds are very far from any easily recognized star-forming region. Figures 1*a* and 1*b* show sketches of the boundaries of these clouds from the atlas by Hodge (1980a) as well as the locations at which the CO spectra were taken and a relative indication of the observed velocity-integrated surface brightnesses. The radio telescope has resolutions (FWHM) of 23″ and 13″ (77 and 43 pc) at the CO(1–0) and CO(2–1) lines, respectively. The temperature scale used in this paper is based on chopper-wheel calibrations and is in the "main beam brightness" system: $T_{\rm mb} = T_A^*/\eta_{\rm mb} = T_R^*\eta_{\rm fss}/\eta_{\rm mb}$. The corresponding forward efficiencies $\eta_{\rm fss}$ are 0.90 and 0.80, and the main beam efficiencies $\eta_{\rm mb}$ are 0.60 and 0.45 at the (1–0) and (2–1) lines, respectively. This "main beam brightness" temperatures scale is appropriate for the present case of well-resolved sources whose sizes are several beamwidths across. Typical system temperatures were 1100 K at 2.6 mm and 1600 K at 1.3 mm, and the spectrometer resolutions were 2.6 and 1.3 km s^{-1}, respectively. The telescope pointing accuracy was checked periodically, and was always found to be within a few arcseconds.

A grid of positions separated by 12″ was set up covering the two dust clouds. Spectra were taken in the two lines simultaneously at a number of these grid points. The observing technique was the "off-on-on-off" cycle (e.g., Casoli et al. 1990), where D268 was in the "on" field and D478 in the "off." Since these clouds are on roughly opposite sides of the galaxy, their spectra are well separated in velocity and a gain of observing time can therefore be realized. Among the other dust clouds observed (and which will be described in detail in another paper) we have also looked for CO emission from several cataloged clouds located within 1′ of the center of M31, including the position of cloud "f" of Rubin & Ford (1971) (D395 + D393 of Hodge 1980a) where a marginal (2 σ) detection of a profile with an amplitude of about 100 mK had been reported by Sandqvist et al. (1989).

3. RESULTS

No CO was detected at any of the positions within 1′ of the nucleus; in particular, our upper limit at the position of cloud "f" is 30 mK (3 σ). On the other hand, we have obtained unambiguous detections of dust clouds further out, typically 2′–4′ (400–800 pc) from the nucleus. As examples we show the results from two of these clouds, D268 and D478. Although the coverage over the two dust clouds is not yet complete, a representative sample of profiles has been obtained. The profiles are quite similar over the area covered by the dust cloud; they diminish in regions where the dust is more filamentary, and disappear below our detection limit (which is typically 50 mK in one channel) when the telescope is positioned beyond the optical boundary of the cloud. Symbols with diameters proportional to the integrated line intensities (profile areas) of the CO(1–0) line are plotted on Figure 1. Figure 2 shows the CO(1–0) line profile at the peak of each cloud together with the CO(2–1) line profile convolved to the same spatial resolution.

4. DISCUSSION

4.1. *Line Intensities and Ratios*

Low values for the observed CO line intensities in galaxy disks and nuclei are usually interpreted as a result of a low "filling factor," i.e., the telescope beam is only partially filled with (optically thick) clouds. However, if this is the explanation for the present result, the area filling factor over the 30 m telescope beam must be quite constant over the dust cloud since the profile intensities do not vary greatly with position over the cloud unless the telescope is pointed beyond the optical boundaries of the clouds, at which point the profiles drop below our detection limit.

The ratio of the integrated CO(2–1) to CO(1–0) line intensities observed at the same resolution (Fig. 2) is 0.20 for the D268 cloud and 0.35 for D478. Actually the central profile for

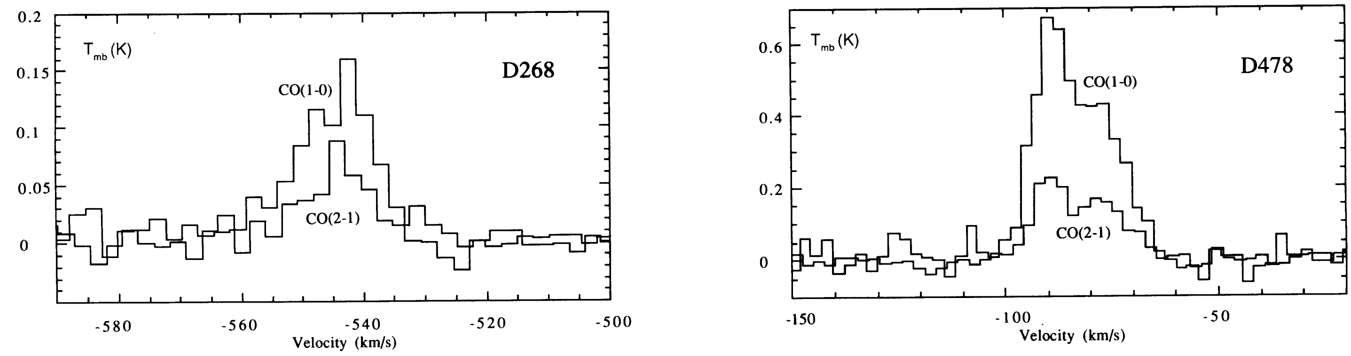

FIG. 2*a*

FIG. 2*b*

FIG. 2.—Typical CO(1–0) and CO(2–1) spectra, from: (*a*) D268, at position −377, −524 in Fig. 1*a*; and (*b*) D478, at position 245, 473 in Fig. 1*b*. The CO(2–1) data have been convolved to the angular resolution of the CO(1–0) data. The temperature scales are $T_{\rm mb}$.

the latter cloud is clearly double-peaked, with ratios of 0.28 and 0.42 for the two components. As such low ratios are exceptional and even unique, we have checked these results by observing the strongest peak in the map of Casoli, Combes, & Stark (1987) for which we found a more classical ratio of 0.68 after convolution to the same resolution. The lower limit for optically thick lines at, e.g., 2.8 K is about 0.45; the only way to explain values lower than this is to conclude that at least the (2–1) line is subthermally excited and thus arises in low-density regions of these molecular clouds (see e.g., Castets et al. 1990).

4.2. *Temperatures*

Since the CO line radiation is evidently not in thermal equilibrium with the cloud gas, the ratios of the CO lines are themselves unfortunately unable to provide us with a value for the kinetic temperature of these molecular clouds. However, there are several indications that these clouds are in fact very cold. First, Suchkov, Allen, & Heckman (1993) have pointed out that cosmic-ray heating is itself sufficient to explain the observed range of molecular cloud densities and temperatures in both starburst and normal galaxies. Their model shows that the temperatures of the ISM can drop to very low values in regions where the cosmic-ray density is substantially lower than that in the Galaxy. The inner disk of M31 is just such a region (Allen 1993) and the model shows that the gas clouds there could indeed have temperatures only a few tenths of a K above the temperature of the cosmic background radiation. It is clearly important to obtain independent observational verification of these low temperatures, and we are carrying out additional observations for this purpose. An apparently contrary piece of evidence is the conclusion by Walterbos & Schwering (1987) based on an analysis of the 12, 60, and 100 μ *IRAS* observations of M31, that the temperatures of the dust in the central region of M31 are around 20 K. However, this refers to dust in the center of the bulge, which is heated by abundant stellar radiation, and it is likely that cooler dust at larger distances from the nucleus would not have been visible to *IRAS*.

4.3. *Mass Surface Densities*

It will now be obvious that, at least in the present case, *the CO line intensities cannot be used as an absolute indicator of the total quantity of molecular gas.* However, the line *widths* carry some information about this if we assume the clouds to be in virial equilibrium.[2] For instance, for the observed part of D478 the radius is roughly $1' = 200$ pc and the line width at half intensity is 25 km s^{-1}. We note that this line width is similar to that of Galactic and Magellanic complexes of the same size (Rubio, Lequeux, & Boulanger 1993). The corresponding virial mass is about 2.4×10^7 $M_\odot$. TheCO(1–0) line luminosity in the same area is 3.1×10^5 K km s^{-1} pc^2, roughly 10 times weaker than for similar Galactic complexes (see Rubio et al. 1993, Figs. 2 and 3).

With our limited spatial coverage it is not yet possible to determine the total amount of molecular gas in the inner disk of M31 with any certainty, but we can make the following rough estimate. From Hodge's (1980b) census we compute that the average dust cloud has a size of about $0''.7 \times 1'.1$, and at a radius of 10′ from the center of M31 there are 0.14 such clouds in each square arcminute; the area filling factor is therefore about 11%. Such "average" clouds (which are a little smaller than D268) are expected to have velocity widths of at least 10 km s^{-1} and virial masses in excess of 10^6 $M_\odot$. The minimum mean surface density in molecular gas is then about 3 $M_\odot$ pc^{-2}. This mass surface density would be insignificant to the dynamics of M31 at a radius of 2 kpc; however, such a contribution from cold molecular gas could become significant if it were to persist to large radii in galaxy disks.

5. CONCLUSIONS

We have detected massive molecular clouds associated with the dust clouds in the inner disk of M31. The clouds have masses similar to Galactic GMC's but are fainter in CO emission by a factor of about 10. The kinetic temperature of these clouds is presently uncertain, but there are indications that they may be only slighly warmer than the cosmic microwave background.

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[2] This assumption may be disputed, especially for the large linear scale of these clouds, but it provides a useful estimate for comparison purposes.

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