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CO EMISSION FROM MOLECULAR CLOUDS IN THE CENTRAL REGION OF M31

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ABSTRACT

We detected ^{12}CO ($J = 1$–0) line emission from a complex of dark cloud located at ~ 250 pc from M31's center, which is the most conspicuous extinction feature within the central few hundred parsecs as observed with B, V, R, and I band CCD observations. The darkest cloud has a 30 pc size, and the virial mass is estimated to be $\sim 8.7 \times 10^5\ M_\odot$, which is the most massive molecular cloud in the bulge of M31. The conversion factor from CO intensity to H_2 column mass is found to be by an order of magnitude greater than that for galactic molecular clouds. The hydrogen mass-to-color excess ratio is also found to be anomalously large.
Subject headings: dust, extinction — galaxies: individual (M31) — ISM: clouds — ISM: molecules

1. INTRODUCTION

Allen & Lequeux (1993) detected CO-line emission from massive molecular clouds of a few hundred parsecs size and a few times $10^7\ M_\odot$ mass in the inner disk of M31 at ~ 2 kpc distance from the nucleus. Although there have been several attempts to map along the major and minor axes (Combes et al. 1977; Stark 1985; Sandqvist, Elfhang, & Lindblad 1989), no detection of CO has been reported in the central few hundred parsecs (e.g., Koper et al. 1991) except for the earlier report of possible detection (Solomon & deZafra 1975). H I observations also indicate a void in interstellar hydrogen (e.g., Brinks & Shane 1984). M31 exhibits a quantity of gas in its inner regions which is more characteristic of early-type galaxies than of other Sb galaxies like the Milky Way. In fact, extensive surveys for optical dark clouds in the central region of M31 have revealed neither a disk nor spiral arms that are related to the outer disk structure (Hodge 1980, 1981).

Recently, we performed a color-excess study of dark clouds in the central region of M31 based on multicolor CCD data taken at the Kiso Observatory, and we reported detection of CO-line emission toward a complex of dark clouds in the central region (Sofue et al. 1993). In this *Letter*, we discuss the physical properties of the clouds based on the CO-line data from the Nobeyama 45 m telescope.

2. OBSERVATIONS

We obtained CCD images filtered in the B, V, R, and I bands on 1992 December 26 with the 1.05 m Schmidt telescope of the Kiso Observatory. The frame with 1000×1018 pixels covered a $12'.53 \times 12'.76$ area. The seeing size was $\sim 4''$ (=13 pc). We obtained several frames with different exposure times, and flat-fielding was applied to each frame, which were finally added. Intensity calibration was made by using star images in a nearby standard field. The darkest area at the SE and NW corners 9′ from the nucleus was subtracted, which yielded an error of $\sim 5\%$ in the sense of underestimating intensity. This error is found to yield an error in the color excess of ~ 0.01 mag. In Figure 1 we show a color-excess map obtained from B and V band frames: the apparent color excess of a cloud is defined by $E_0(B-V) = (B-V)_{\rm cloud} - (B-V)_{\rm bg}$, where subscripts "cloud" and "bg" denote values for the cloud and its surrounding smooth background, respectively.

Conspicuous in Figure 1 are dark clouds at ΔR.A. $\sim -20''$ and ΔDecl. $\sim 75''$, where ΔR.A. and ΔDecl. are offsets from the nucleus at R.A. = $00^h40^m00^s.1$, Decl. = $40°59'42''.7$ (1950) (NED 1992[3]). The outline of the clouds had been listed as D382, D384, and D395 by Hodge (1981). The size of each cloud is typically 10″ (33 pc in diameter). The apparent color excess of the darkest cloud is measured to be $E_0(B-V) = 0.10 \pm 0.01$ and $E_0(B-I) = 0.22 \pm 0.01$. The intrinsic color excess due to a cloud, which can be related to interstellar extinction, is derived by correcting for the foreground emission of the bulge, which is assumed to contribute by a half to the total bulge emission. Then, since $E_0(B-V)$ and $E_0(B-I)$ are small enough, the clouds' color excess may be approximately double the apparent excess: $E(B-V) = 0.20$ and $E(B-I) = 0.44$. Their ratio, $E(B-V)/E(B-I) \sim 0.45$, indicates a normal interstellar extinction (Walker 1987).

A number of dark clouds and filaments are distributed in the central few hundred parsecs (Fig. 1). Their distribution traces a "barred face-on" spiral, apparently not related to the outer disk (see Sofue et al. 1993 for more detailed discussion of optical features). They also show a good coincidence with the off-plane face-on spirals observed in the Hα emission (Ciardullo et al. 1988). These facts indicate that the dark clouds are off-plane objects, probably on a plane perpendicular to the line of sight. Then, the distance of the cloud from the nucleus is estimated to be 250 pc, and its height from the Galactic plane ~ 150 pc. However, we cannot deny the possibility that the clouds lie in the disk plane, in which case their distance from the nucleus is ~ 800 pc.

Deep ^{12}CO ($J = 1$–0)-line observations of the central region were made using the Nobeyama 45 m telescope in 1992 December and 1993 February during the course of CO-line study of nuclei in early-type galaxies. The antenna had a HPBW of 15″ (=50 pc) at 115.271 GHz, and the aperture and main-beam efficiencies were $\eta_a = 0.35$ and $\eta_{\rm mb} = 0.50$, respectively. The intensity scale used in this *Letter* is the main-beam brightness temperature which is related to the antenna temperature by $T_{\rm mb} = T_A^*/\eta_{\rm mb}$. We used an SIS receiver of system noise temperature of ~ 500 K, combined with a 2048 channel acousto-optical spectrometer with a velocity coverage of 650 km s^{-1}.

We mapped six positions toward the dark-cloud complex as

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[3] NED (NASA/IPAC Extragalactic Database) is operated by JPL, California Institute of Technology, under contract by NASA.

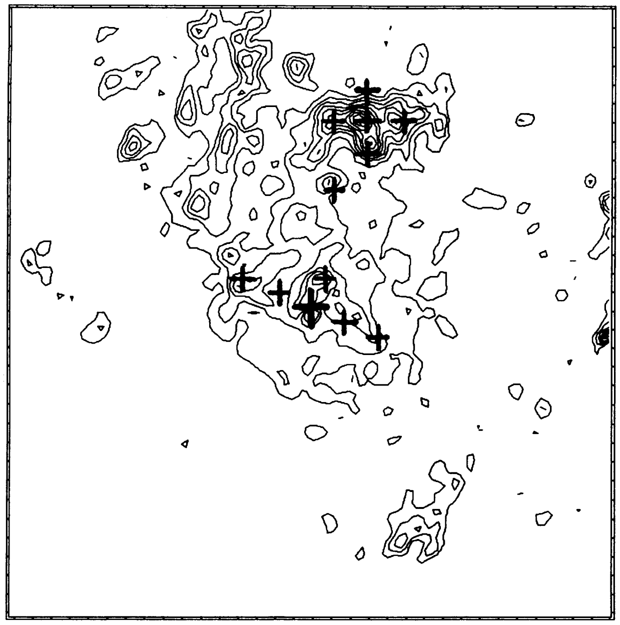

FIG. 1.—Color excess map of $E(B-V)$ for the central $4' \times 4'$ region. The contours are drawn at interval of 0.011 mag, starting at 0.011 mag, in excess over the background. Note a dark-cloud complex at 1.'3 (250 pc) north of the nucleus. Crosses indicate positions of CO line observations, and the large cross indicates the nucleus.

indicated by the northern crosses in Figure 1. We also obtained several spectra along faint dark lanes near the nucleus at P.A. = 67° (central crosses in Fig. 1), which is associated with a nuclear ministellar bar (Sofue et al. 1993). The reference off points were taken at $\pm 5'$ east and west, where no significant dark clouds was found. The on-source total integration time was 1.5 hr per point, and baseline fitting with third-order polynomials was applied. After binding up every 32 channels, we obtained spectra with a velocity resolution of 10 km s^{-1} and rms noise of 10–20 mK T_{mb}.

3. RESULTS

The obtained CO spectra toward the northern dark clouds are shown in Figure 2*a*. The CO line appears to have been detected nearly all positions at a velocity of $V_{LSR} \simeq -220$ km s^{-1}, although the detection is only 2–3 σ level. In order to increase the signal-to-noise ratio, we integrated the six spectra to get a composite spectrum as shown in Figure 2*b*, which now shows the detection at $\sim 5\ \sigma$ level. The velocity agrees with that derived from the [O II] and [Ne III] lines at approximately the same position (Ciardullo et al. 1988). The velocity width at half-maximum of the CO line is $\sigma_v \sim 30$ km s^{-1}, and the integrated intensity is $\sim I_{CO} \sim 9 \pm 2$ K km s^{-1} toward the dark cloud. No significant emission was detected along the line crossing the nucleus (Fig. 2*c*).

The darkest cloud in the northern complex (Fig. 1) has an optical size of 10″ in diameter, or the radius is $r \sim 17$ pc. For the velocity width of $\sigma_v \sim 30$ km s^{-1}, the virial mass of the cloud can be estimated as $M_{vir} \sim (\sigma_v/2)^2 r/G \sim 8.7 \times 10^5\ M_\odot$, where G is the gravitational constant. The total mass involved in the complex is estimated to be a few times $10^6\ M_\odot$. Thus, the dark cloud complex has a mass comparable to a giant molecular cloud. As usual for a virial-mass estimation, the derived value contains an error of a factor of 2, which also applies to related values derived below. We stress that the complex is most conspicuous, and therefore probably most massive, within the central few hundred parsecs of M31's nucleus. This shows a striking contrast to the nuclear disk of our Galaxy, where giant molecular complexes by one or two orders of magnitude more massive have been observed (e.g., Bally et al. 1987).

The column density of H_2 of this cloud is then estimated to be $N_{H_2} \sim M_{vir}/(\pi r^2) \sim 6.3 \times 10^{22}$ H_2 cm^{-2}. Since the beam area is slightly larger than the apparent optical size of the cloud, the true CO intensity (I_{CO}) can be estimated from observed intensity ($I_{CO,obs}$) by correcting for the beam-dilution factor of about $f \sim (10''/15'')^2$, and we obtain $I_{CO} = I_{CO,obs}/f \sim$ 20 K km s^{-1}. From these, we derive a conversion factor from CO intensity H_2 column density as $X = N_{N_2}/I_{CO} \sim 3.1 \times 10^{21}$ H_2 cm^{-2}/K km s^{-1} ($= 49\ M_\odot$ pc^{-2}/K km s^{-1}). This value is by a factor of 10 greater than that for molecular clouds in our Galaxy as estimated from a similar virial-mass method: $X_{Gal} \sim 3.6 \times 10^{20}$ H_2 cm^{-2}/K km s^{-1} (Sanders et al. 1984).

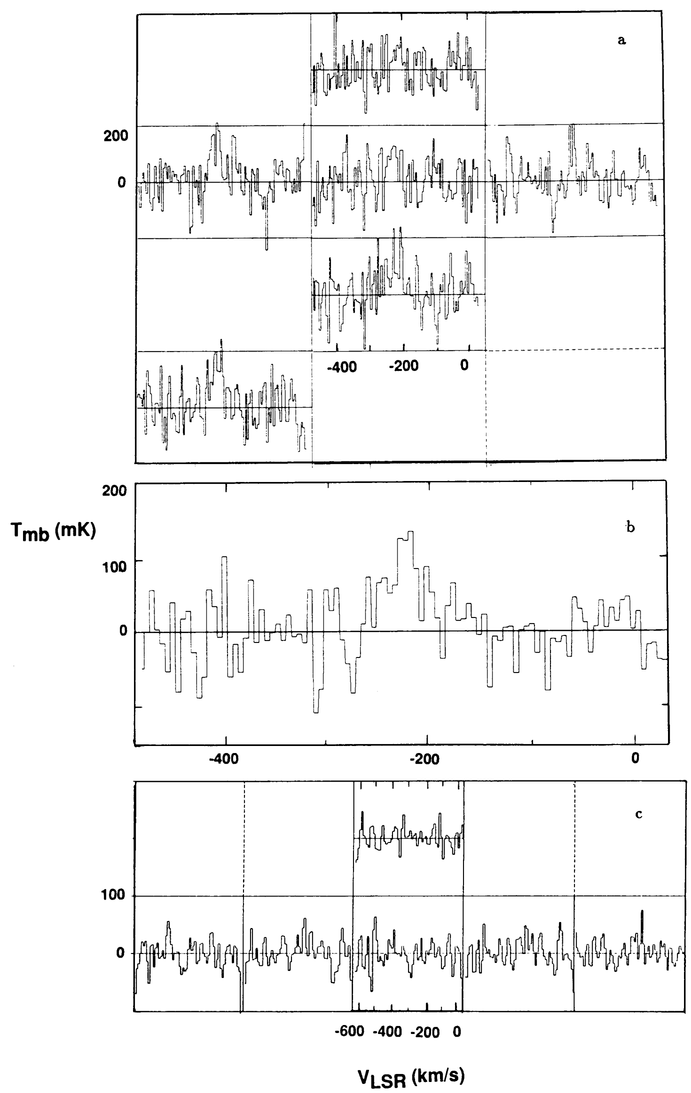

FIG. 2.—(*a*) CO-line spectra observed toward the nuclear dark clouds for positions indicated by the northern six crosses in Fig. 1*b*. (*b*) Composite spectrum from (*a*). (*c*) Spectra for positions near the nucleus indicated by the central six crosses in Fig. 1.

The gas-to-color excess ratio is obtained as $N_{H_2}/E(B-V) \simeq 6.3 \times 10^{23}$ atoms cm^{-2} mag^{-1}. This is almost by two orders of magnitude greater than that for intercloud value in the solar vicinity, $\sim 6 \times 10^{21}$ atoms cm^{-2} mag^{-1}, which might increase significantly for dust in dense clouds (Savage & Mathis 1979).

4. CONCLUSIONS

CO emission has been detected toward a dark cloud complex at 250 pc distance from the center of M31, while no CO was detected toward the nucleus. The darkest cloud in the complex has a size of ~ 30 pc and a virial mass of $8.7 \times 10^5 M_\odot$ (with an error of factor of 2), which is the most massive cloud near the nucleus. The extremely small amount of molecular gas in the central region shows a contrast to the molecular gas-rich nuclear disk of our Galaxy. The gas-to-CO intensity ratio, hence the conversion factor from CO intensity-to-molecular hydrogen column mass, is estimated to be an order of magnitude greater than the the galactic value. This indicates a smaller heavy element-to-gas ratio in the M31 center. The gas-to-color excess ratio was found to be almost by two orders of magnitude greater than the intercloud galactic value. This might indicate that the dust-to-CO ratio in the bulge of M31 is significantly smaller than that in the solar vicinity.

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