CO EMISSION FROM MOLECULAR CLOUDS IN THE CENTRAL REGION OF M31
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ABSTRACT

We detected $^{12}\text{CO}(J = 1 - 0)$-line emission from a complex of dark cloud located at about 250 pc from M31’s center, which is the most conspicuous extinction feature within the central few hundred pc as observed in $B, V, R, I$-band CCD imaging. 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: Dark clouds – CO emission – Galaxies; individual (M 31) – Interstellar extinction – Molecular clouds.

I. INTRODUCTION

Allen and Lequeux (1993) detected CO-line emission from massive molecular clouds of a few hundred pc size and a few $\times 10^7 M_\odot$ mass in the inner disk of M31 at $\sim 2$ 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 et al. 1989), no detection of CO has been reported in the central few hundred pc (e.g., Koper et al. 1991) except for the earlier report of possible detection (Solomon and deZafra 1975). HI observations also indicate a void in interstellar hydrogen (e.g., Brinks and 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 multi-color CCD data taken at the Kiso Observatory, and reported detection of CO-line emission toward a complex of dark clouds in the central region (Sofue et al. 1993). In this paper, we discuss the physical properties of the clouds based on the CO-line data from the Nobeyama 45-m telescope.

II. OBSERVATIONS

We obtained CCD images filtered in the $B, V, R$- and $I$-bands on December 26, 1992 with the 1.05-m Schmidt telescope of the Kiso Observatory. The frame with 1000 $\times$ 1018-pixels covered a $12.53 \times 12.76$ area. The seeing size was about 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 about 5% in the sense of underestimates of intensity. This error is found to yield an error in the color excess of about $\sim 0.01$ mag.. In Fig. 1 we show a color-excess map obtained from $B$ and $V$-band frames: the apparent color excess of a cloud is defined by $E_0(B - V) = (B - V)_{\text{cloud}} - (B - V)_{\text{bg}}$, where subscripts ‘cloud’ and ‘bg’ denote values for the cloud and its surrounding smooth background, respectively.

Conspicuous in Fig. 1 are dark clouds at $\Delta RA \sim -20''$ and $\Delta Dec \sim 75''$, where $\Delta RA$ and $\Delta Dec$ are offsets from the nucleus at RA = 00h 40m 00.1s, Dec = 40°59′42.7″ (1950)(NED 1992). 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 pc (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 Ho 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 about 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 about 800 pc.

Deep $^{12}$CO($J = 1 − 0$)-line observations of the central region were made using the Nobeyama 45-m telescope in December 1992 and February 1993 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 $\eta_{mb} = 0.50$, respectively. The intensity scale used in this paper is the main-beam brightness temperature which is related to the antenna temperature by $T_{mb} = T_A/\eta_{mb}$. We used an SIS receiver of system noise temperature of of about 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 indicated by the northern crosses in Fig. 1. We also obtained several spectra along faint dark lanes near the nucleus at PA=67$^\circ$, which now shows the detection at about 5$''$ crossing the nucleus (Fig. 2c). We also mapped six positions toward the dark-cloud complex as indicated by the northern crosses in Fig. 1. We also obtained several spectra along faint dark lanes near the nucleus at PA=67$^\circ$, which now shows the detection at about 5$''$ crossing the nucleus (Fig. 2c). We also obtained several spectra along faint dark lanes near the nucleus at PA=67$^\circ$, which now shows the detection at about 5$''$ crossing the nucleus (Fig. 2c).

III. RESULTS

The obtained CO spectra toward the northern dark clouds are shown in Fig. 2a. The CO line appears to have been detected nearly all positions at a velocity of $V_{LSR} \sim -220$ km s$^{-1}$, although the detection is only 2 to 3$\sigma$ level. In order to increase the signal-to-noise ratio, we integrated the six spectra to get a composite spectrum as shown in Fig. 2b, which now shows the detection at about 5$\sigma$ level. The velocity width at half maximum of the CO line is $\sigma_v \sim 30$ km s$^{-1}$, and the integrated intensity is about $I_{CO} \sim 9 \pm 2$ K km s$^{-1}$toward the darkest cloud. No significant emission was detected along the line crossing the nucleus (Fig. 2c).

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 two, 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 pc 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 to H$_2$column density as $X = N_{H_2}/I_{CO} \sim 3.1 \times 10^{21}$ H$_2$cm$^{-2}$/K km s$^{-1}$ (Sanders et al. 1984). This value is by a factor of ten 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).

The gas-to-color excess ratio is obtained as $N_{H_2}/E(B − V) \sim 6.3 \times 10^{23}$ atoms cm$^{-2}$mag$^{-1}$. This is almost by two orders of magnitude greater than that for inter-cloud 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 and Mathis 1979).

IV. CONCLUSION

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 about 30 pc and a virial mass of $8.7 \times 10^5 M_\odot$ (with an error of factor two), 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 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 inter-cloud 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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Figure Captions
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.

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