

Face-on Barred Spiral Structure of Dark Clouds in M31's Bulge

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Abstract

By image processing and color-excess analyses of B , V , R , and I -band CCD images of the central region of M31 taken with the Kiso 105-cm Schmidt telescope, we found a bar of 200-pc length. We also found a more extended “face-on” spiral feature of dark clouds, which appears to be connected to this bar and is probably an out-of-plane structure. $^{12}\text{CO}(J=1-0)$ -line emission was detected from the dark clouds using the Nobeyama 45-m telescope, and the virial mass of individual clouds was estimated to be $\sim 10^6 M_{\odot}$. The CO intensity-to-virial mass ratio is anomalously small, and thus is the color excess-to-mass ratio, which indicates a low temperature and a small amount dust per unit gas mass in the cloud, respectively. This implies that the molecular clouds in the central few hundred pc of M31 are more “primeval”, suggesting low star formation and low dust supply. We propose a possible scenario for the origin of a face-on spiral containing such gas on the basis of a ram-pressure accretion model of stripped gas clouds from the companion galaxies.

Key words: CO line — Dark clouds — Galaxies: individual (M31) — Interstellar dust — Nuclei of galaxies

1. Introduction

The optical photometry of the central region of M31 showed an ellipsoidal bulge without indication of a disk structure (Kinman 1965). Extensive surveys for optical dark clouds in the central region of M31 have revealed neither a disk structure nor spiral arms that are related to the major disk of M31 (Johnson, Hanna 1972; Hodge 1980; Gallagher, Hunter 1981; McElroy 1983). On the other hand, CCD imaging of the $\text{H}\alpha$ emission of M31's bulge has revealed peculiar spiral patterns of ionized gas, which suggested an off-plane ejection of gas driven by wind from bulge stars (Ciardullo et al. 1988). Far-infrared observations with the IRAS have indicated a central concentration of warm dust (Habing et al. 1984).

In spite of the indication of interstellar activity, no significant detection of molecular or atomic hydrogen gas has been reported, indicating a lack of interstellar hydrogen in the central region based on CO-line observations (Combes et al. 1977; Stark 1985; Koper et al. 1991) and HI observations (Roberts, Whitehurst 1975; Brinks, Bajaja 1986). In this respect, the central region of M31 exhibits early-type characteristics (Gallagher, Hunter 1981). These facts put M31 among exceptions in which little molecular gas is present in the nuclear region, unlike other Sb galaxies, like the Milky Way (Dame

et al. 1990) or NGC 891 (Garcia-Brillo et al. 1992; Sofue, Nakai 1993).

In this paper we consider CCD images in the B , V , R , and I -bands of M31's bulge to which contrast-enhancement techniques have been applied, in order to study the detailed morphology in the central region. We also report on the detection of CO line emission toward several dark clouds, and discuss their mass and kinematics.

2. Optical Bar and Dark Clouds

2.1. CCD Images

CCD images filtered in the B , V , R , and I -bands were taken on 1992 December 26 with the 1.05/1.50-m Schmidt telescope of the Kiso Observatory at the $f/3.0$ primary focus. The detector was the TC 215-1K (=KCCD 2; Kiso CCD No.2), which is a 1000×1018 device. The pixel size was $0''.752$, which corresponded to 2.5 pc at 690 kpc distance from the M31 center, so that the frame covered the central $12'.53 \times 12'.76$ (2.52×2.56 kpc²). The seeing size was estimated to be about $4''$ (=13 pc). We obtained several frames with different exposure times at each band; a flat-fielding was applied to each frame. The data were added so that the

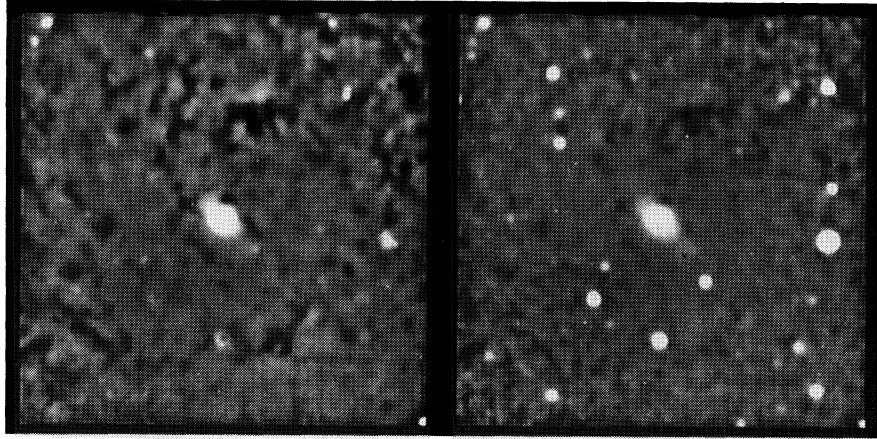


Fig. 1. Background-filtered B (left: stars are subtracted) and I -band (right panel) images of the central $4'3 \times 4'3$ region of M31 taken with a CCD equipped on the Kiso 105-cm Schmidt telescope. The original images were divided by Gaussian-smoothed images with HPBW of 10 pixels ($7''.5$) (“unsharp-divided” images). The darkest region is 0.18 mag darker than the average in B band, and 0.07 mag in the I band, which, however, do not represent a true darkening, because the smoothed cloud structures have been subtracted as well. For a quantitative discussion of extinction, see the color excess maps in figure 4. (N to the top; E to the left.)

images that we use have total exposure times of 570, 110, 55, and 40 s for the B , V , R , and I -bands, respectively. An intensity calibration was made by using star images of the SA 95 standard field. The reduction has been made by using the standard IRAF package.

The sky subtraction was rather ambiguous because of the extended emission of the M31 disk. However, the usual type contrast-enhanced (background-filtered) images, which we use to identify dark clouds, are not affected by the ambiguity of sky subtraction, since the background extended emission is subtracted. In order to estimate color indexes, sky subtraction was necessary; we simply subtracted the darkest sky at the SE and NW corners $9'$ from the nucleus, which yielded intensity excess over that of the darkest sky in the same frames. The central region of the bulge within $2'$ of the nucleus, in which we are interested, was found to have CCD counts an order of magnitude greater than that at this darkest corner; this simple subtraction resulted in an error of about 5% of the intensity in each band in the sense of an underestimate of the intensity. We actually compared the results (e.g., color excesses) with those obtained from images without applying the sky subtraction, but found almost no significant difference. We applied contrast-enhancing techniques in order to produce a differential intensity distribution, in which the error is reduced to about 2%, or 0.02 mag.

The color excess of a cloud is defined as

$$\begin{aligned} E(B - V) &= (B - V)_{\text{cloud}} - (B - V)_{\text{bg}} \\ &= (B_{\text{cloud}} - B_{\text{bg}}) - (V_{\text{cloud}} - V_{\text{bg}}), \end{aligned} \quad (1)$$

where the subscripts ‘cloud’ and ‘bg’ denote the values

for the cloud and its surrounding smooth background, respectively. If there exist errors of δ_B and δ_V in the intensities (I_B , I_V) (such as due to ambiguous sky subtraction), the error involved in the color excess is estimated to be

$$\begin{aligned} \delta_E &\simeq 2.5 [(\delta_B/I_{B,\text{cloud}} - \delta_B/I_{B,\text{bg}})^2 \\ &\quad + (\delta_V/I_{V,\text{cloud}} - \delta_V/I_{V,\text{bg}})^2]^{1/2} \\ &\sim 2.5 [(\delta\Delta/I_{\text{bg}}^2)_B^2 + (\delta\Delta/I_{\text{bg}}^2)_V^2]^{1/2}, \end{aligned} \quad (2)$$

where $\Delta = I_{\text{cloud}} - I_{\text{bg}} \ll I_{\text{bg}}$. Hence, the error in E is estimated to be $\delta_E \sim 0.009$ mag. The errors due to read-out noise of the chip are estimated to be much smaller.

2.2. An Optical Bar

The original images do not clearly show up the fine features, which are embedded in the bright central bulge. Hence, we applied contrast-enhancing techniques, as described by Sofue (1993), in order to subtract the background diffuse emission. First, we made use of the background-filtering technique (BGF; Sofue, Reich 1979), which is an equivalent method to the unsharp-masking method. We subtracted bright stars and the nucleus, and convolved the resultant image with a Gaussian function with HPBW=10 pixels. Then, the original image was divided (not subtracted) by the smoothed image, yielding a BGF image. This is similar to the unsharp-masking method, but should rather be called an “unsharp-dividing” method. The unsharp-dividing gives a contrast-enhanced ratio of intensity measured in magnitudes, and is convenient for discussing such features as

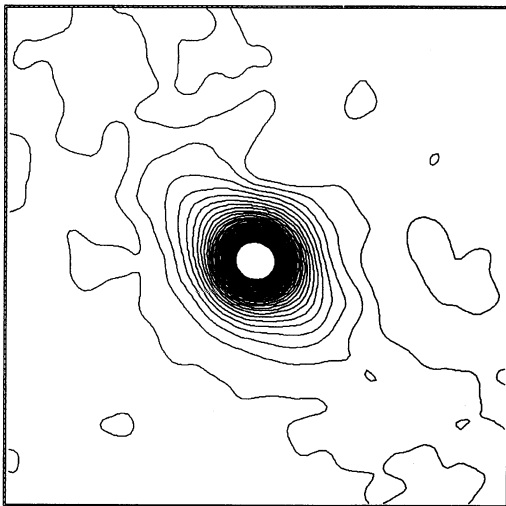


Fig. 2. BGF (unsharp-divided) image of the mini bar in R band. The central $1'.25$ squared region is shown. Contours are drawn every -0.021 mag starting at -0.01 mag relative to the smooth background.

extinction by dark clouds silhouetted against the background; the result does not depend on the background intensity. (Note, on the other hand, that unsharp-masking gives subtraction residuals, which depend on the subtracted background intensities, so that a cloud would appear darker if it is in front of bright background, and vice versa.) Figure 1 shows the thus-obtained BGF (unsharp-divided) images.

First of all, figure 1 reveals a bright bar-like feature near to the nucleus. The bar is elongated in the direction of $PA = 45^\circ$, and the major-axis length is about $1'$ ($= 200$ pc). Figure 2 shows an enlarged image of the bar in the R band. The major-to-minor axial ratio is approximately 3.0, much greater than that of the central-bulge component (axial ratio of 1.3 at $PA = 55^\circ$; Kinman 1965). This fact implies that the bar feature is a distinct structure superposed on the more round-shaped bulge component.

The apparently bar-like feature may be either due to a nearly edge-on view of a small (rotating) stellar disk, or a real bar structure. If it is a perfect edge-on disk, the thickness is approximately 60 pc for a radius of about 100 pc (diameter $1'.0$). However, if it lies in the same plane as the major M31 disk ($i = 77^\circ$; tilt angle of 13° from the line of sight), the thickness must be less than 10 pc, which is unrealistically thin. Therefore, we may reasonably assume that the feature is a real bar structure.

The V -band flux from this bar (after subtracting the bulge component) is estimated to be $\sim 5\%$ of the total flux within 100 pc ($30''$) radius of the center. The to-

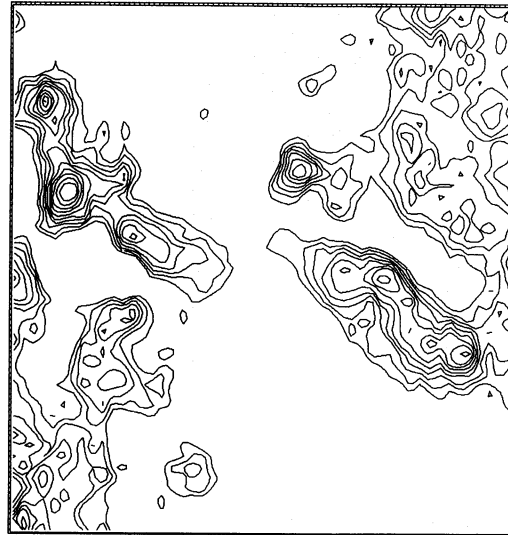


Fig. 3. Θ -relief B band image of dark lanes associated with the central "mini bar" near to the nucleus of M31. The central $1'.25$ squared region (the same as figure 2) is shown. The contours are drawn every 0.01 mag starting from 0.01 mag relative to the background (darker toward contour peaks); more quantitative information can be obtained from the color excess maps in figure 4.

tal magnitude of the M31 bulge in $30''$ of the nucleus is estimated to be 8.0 mag in the V band, and the galactic-extinction-corrected magnitude of 7.7 V mag. This yields an absolute magnitude of -16.5 mag, and 3×10^8 solar luminosity, for an assumed distance of 690 kpc. For a possible mass-to-luminosity ratio of about 5 (in solar units) for the bulge region, we obtain a total mass of $\sim 1.5 \times 10^9 M_\odot$. On the other hand, the dynamical mass of the bulge within 100 pc ($30''$) can be estimated as $M_{\text{dyn}} \sim r(v^2 + \sigma^2)/G \sim 7 \times 10^8 M_\odot$ for an ellipsoid with a velocity dispersion σ of 170 km s^{-1} and a rotation v of 40 km s^{-1} (Kormendy 1988), where G is the gravitational constant. This dynamical mass leads to a mass-to-luminosity ratio of 2 (in solar units). We may thus estimate that the bar has a mass of $\sim 2\text{--}4 \times 10^7 M_\odot$.

2.3. Dark Lanes along the Bar

This bar is associated with dark lanes on its leading edges with respect to the rotation sense of the galaxy (anti-clockwise). In order to show up the dark lanes, we applied another contrast-enhancing technique, called the Θ relief method (Sofue 1993). The original image was rotated by 10° around the nucleus, and the rotated image was subtracted from the original, which yielded a differentiation in the azimuthal direction and enhances radial features embedded in the bright background. Figure 3 shows the Θ relief image in the B band for the

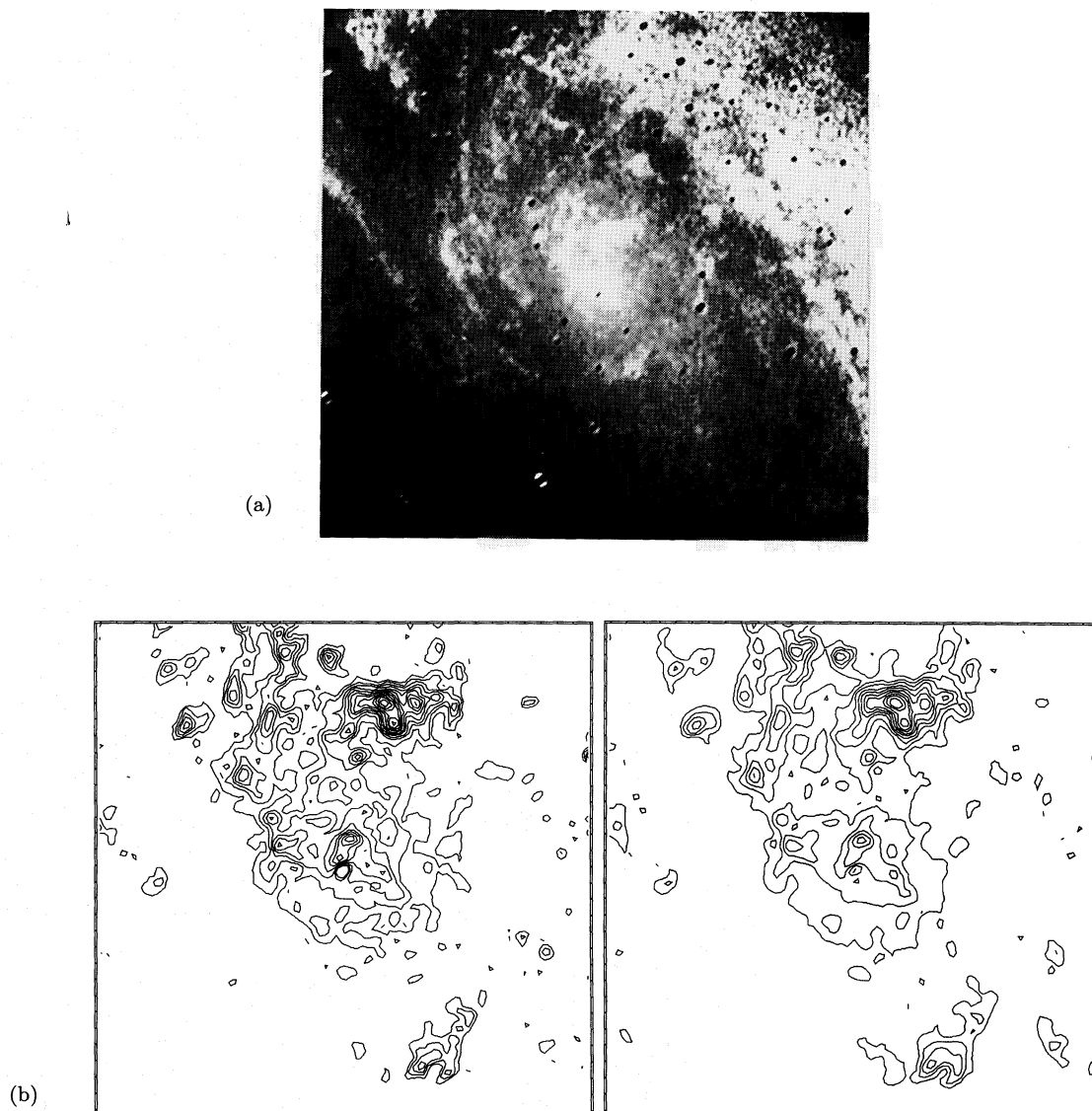


Fig. 4. (a) Gray-scale map of the intensity ratio between B and I images (equivalent to $B - I$, but in a linear intensity scale) for the central 12.5 squared region of M31. Darker regions are redder, and white bluer. Note the face-on spiral feature of dark clouds coinciding with the $H\alpha$ spiral feature observed by Ciardullo et al. (1988). (b) Color excess contour maps for $E(B - V)$ (left panel) and $E(B - I)$ (right panel). The central 3.76 squared region is shown. The contours are drawn at intervals of 0.016 mag, starting at 0.016 mag, in excess over the background color index of the bulge. The reddest cloud has an index excess of $E(B - V) = 0.10$ and $E(B - I) = 0.22$.

central 2.5×2.5 . The dark lanes run in the direction at $PA = 60^\circ$, and are slightly curving in the trailing sense with respect to M31's rotation. The length of each dark lane is about $30''$ (100 pc). In order to clarify whether these dark features are due to interstellar extinction, we obtained the color excess maps shown in figure 4. The dark lanes are significantly redder than the surrounding regions with an excess in the color index of $E(B - V) = 0.035$ and $E(B - I) = 0.065$. The ratio of the two excesses, $E(B - V)/E(B - I) \sim 0.5$, confirms that the dark lanes are due to interstellar absorption (Walker

1987). The bright mini bar has about the same color and, therefore, about the same population as the bulge stars.

In order to estimate the 'true' color excess of the dark lanes, which can be related to interstellar extinction, we need to correct for the foreground emission of the bulge. For this we simply assume that the contribution of the foreground emission is half of the total bulge emission. Then, the dark lanes' color excess (with respect to the bulge light behind the lanes) is estimated to be about twice the above-obtained apparent excess

values: $E'(B - V) \simeq 2E(B - V) = 0.07$; $E'(B - I) \simeq 2E(B - I) = 0.13$. If we assume a "normal" conversion formula from the color excess to column density of hydrogen gas, we can estimate the column density of hydrogen atoms to be 4×10^{20} atoms cm^{-2} toward the lane, where we used the empirical relation obtained for interstellar matter in the solar vicinity; $N(\text{H} + \text{H}_2)/E'(B - V) \sim 6 \times 10^{21}$ atoms $\text{cm}^{-2} \text{mag}^{-1}$ (Savage, Mathis 1979). From the column mass, we estimate the approximated mass of the dark lanes to be only $\sim 10^4 M_\odot$. However, as discussed in section 3 in detail, this estimate does not necessarily give the right value in view of a much smaller column mass which is estimated from the dynamical mass of the clouds using molecular line-width information.

2.4. Dark Clouds along "Face-on Spirals"

The most conspicuous in figure 3 are dark patches with high $E(B - V)$ in the northern region of the nucleus, located at $\Delta\delta \sim 75''$, $\Delta\alpha \sim -20''$, where $\Delta\delta$ and $\Delta\alpha$ are offsets in declination and right ascension with respect to the nucleus, respectively. These "red" patches are clearly identified with dark patches in the contrast-enhanced image in figure 1. The size of individual clouds is typically $15''$ (50 pc). The high color excess indicates interstellar extinction by dust; we may call these patches dark (dust) clouds. The excess in the color index of the clouds over that of the bulge reaches about $E(B - V) = 0.10$ and $E(B - I) = 0.22$ at the darkest (reddest) cloud. This indicates again normal interstellar extinction (Walker 1987). For the same assumption as above, we estimated the clouds' color excess to be $E'(B - V) = 0.20$ and $E'(B - I) = 0.44$, which corresponds to a hydrogen column density of about $N(\text{H} + \text{H}_2) \sim 1.2 \times 10^{21}$ atoms cm^{-2} . For a size of 50 pc, its mass is estimated to be $\sim 3 \times 10^4 M_\odot$. This value is consistent with that obtained by Gallagher, Hunter (1981).

Besides these conspicuous clouds, a number of dark clouds are distributed over the $2'$ -radius region around the nucleus, especially in the NE to N and in SW. The distribution of these dark clouds appears to trace spiral arms, which look rather "face-on." This spiral pattern appears to be independent of the major spiral structure of the M31 disk that is closer to edge-on at an inclination angle of 77° . We point out that this face-on spiral distribution shows a good coincidence with the nearly face-on spiral pattern observed in the $\text{H}\alpha$ emission (Ciardullo et al. 1988). We mention here that the dark clouds recognized in our analysis are not associated with any star-forming regions, as is shown from an inspection of the B -band images.

3. CO-Line Emission

3.1. CO Observations

In order to investigate the mass and kinematics of the dark clouds found in the CCD images, we performed ^{12}CO ($J = 1-0$) line observations using the Nobeyama 45-m telescope. The result and observational detail have been reported in Sofue, Yoshida (1994). We briefly summarize the result.

3.2. Upper Values for CO Emission along the Mini Bar

We observed the dark lanes associated with the mini bar at $X = -30''$, $-15''$, $0''$, $15''$, $30''$ and $Y = 0''$ as well as at $X = 0''$, $Y = 15''$, where X and Y are coordinates taken along a line crossing the nucleus at $\text{PA} = 67^\circ$ (X positive toward NE, and Y positive toward NW). No significant emission was detected, yielding an upper limit of about 20 mK in T_{mb} (Sofue, Yoshida 1994). For an assumed velocity width of about 100 km s^{-1} , this gives an upper limit to the molecular hydrogen mass of $\sim 1 \times 10^5 M_\odot$ within the observed area (mini bar). The weaker CO emission compared to the northern dark clouds (as described below) is consistent with the smaller $E(B - V)$ and $E(B - I)$ values near to the mini bar, which indicates less extinction and, therefore, a smaller amount of molecular gas. We mention, however, that we cannot deny the possibility of non-detection due to a possibly broad line profile, which often occurs near to the nucleus due to a large velocity dispersion and high rotation velocity.

3.3. CO Emission from Northern Dark Clouds

We observed several positions around the northern dark clouds. The CO emission has been detected at all positions at $T_{\text{mb}} = 100$ to 180 mK except for D (Sofue, Yoshida 1994). The mean velocities of the emission are about -220 km s^{-1} at around point C, and about -250 km s^{-1} at F. These velocities agree with the velocities of ~ -200 to -250 km s^{-1} derived from the optical spectroscopy of the $[\text{O II}]$ and $[\text{Ne III}]$ lines at $\sim 80''$ from the nucleus at $\text{PA} = -7^\circ$ and -38° (to NE), respectively (Ciardullo et al. 1988).

The darkest cloud in the northern complex has an optical size of $10''$ in diameter, or a radius of $r \sim 17$ pc. A CO velocity width, $\sigma_v \sim 30 \text{ km s}^{-1}$, has been observed, which yields a virial mass of the cloud of $M_{\text{vir}} \sim 9 \times 10^5 M_\odot$. The total mass involved in the dark complex is then estimated to be some $10^6 M_\odot$. Thus, the dark cloud complex has a mass that is comparable to a giant molecular cloud. We stress that the dark 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 that are one or two orders of magnitude more massive have been observed.

The column density of H_2 of this cloud is then estimated to be $N_{\text{H}_2} \sim 6 \times 10^{22} \text{ H}_2\text{cm}^{-2}$. After applying a correction for the beam-dilution effect we obtain the CO intensity toward the dark cloud to be $I_{\text{CO}} \sim 20 \text{ K km s}^{-1}$. From these, we derive a conversion factor from the CO intensity to the H_2 column density as $X = N_{\text{H}_2}/I_{\text{CO}} \sim 3 \times 10^{21} \text{ H}_2 \text{ cm}^{-2}/(\text{K km s}^{-1}) [= 50 M_{\odot} \text{ pc}^{-2}/(\text{K km s}^{-1})]$. 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: $\sim 3.6 \times 10^{20} \text{ H}_2\text{cm}^{-2}/(\text{K km s}^{-1})$ (Sanders et al. 1984). The anomalous conversion factor is similar to that observed in the Small Magellanic Clouds (Rubio 1991); also, the weak CO emission is similar to that observed in molecular clouds in the Large Magellanic Cloud (Booth, de Glauw 1991).

We also find that the gas-to-color excess ratio is anomalous: $N_{\text{H}_2}/E(B - V) \simeq 6 \times 10^{23} \text{ atoms cm}^{-2} \text{ mag}^{-1}$. This is greater by two orders of magnitude than that for the inter-cloud value in the solar vicinity, $\sim 6 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1}$, which might increase significantly for dust in dense clouds (Savage, Mathis 1979). The observations indicate an anomalously small amount of molecular gas in M31's bulge compared to those observed in the central few hundred pc in other Sb galaxies like the Milky Way (Dame et al. 1990) and NGC 891 (Garcia-Brillo et al. 1992; Sofue, Nakai 1993). In view of such a small amount of molecular gas, it is not surprising that no indication of star formation can be recognized from an inspection to the B - and V -band images (figure 1).

The small CO intensity-to-gas mass ratio indicates that the heating source of the clouds is lacking, and, hence, the star-formation rate in the central few hundred pc is very low. The anomalously small color excess indicates that the dust content per unit mass of the gas is small and, hence, the gas is dust deficient. We may, therefore, conclude that the molecular clouds in the central region are more "primeval" and appear to be new comers rather than a long-living polluted gas. From this fact, we suggest that the gas clouds could have originated by infall from external galaxies of the Magellanic type, which we discuss in the next section in some detail.

4. Discussion

The N to NE and SW dark clouds in M31's center appear to trace a "face-on" spiral in positional as well as morphological coincidence with those of ionized gas (Ciardullo et al. 1988). These spiral features appear to be connected to the more central bar-like structure, which is

associated with dark lanes on its leading edges. All these suggest a face-on barred spiral structure comprising dark clouds as well as a central mini stellar bar.

The origin of such a barred spiral structure of ionized as well as molecular gases in the central few hundred pc, which is highly-tilted with respect to the M31 main disk, is a mystery, providing an interesting subject. A possible scenario involves ejection of ionized gas from M31's bulge via a galactic wind which was driven by energy pumped into the interstellar matter by supernova explosions (Ciardullo et al. 1988). However, since the central 1 kpc region contains very little gas, and no nuclear gaseous disk is present (Sofue, Yoshida 1994), such an explosion-driven wind must blow spherically; it thus seems difficult to collimate the wind in the out-of-plane spiral.

We recently proposed a ram-pressure stripping-and-accretion model of gaseous debris from the companions, M32 and NGC 205 (Sofue 1994). A merger galaxy, which is suggested from the existence of double nuclei (Lauer et al. 1993), could be an alternative origin of the gaseous debris. In this scenario we assume that M32 and NGC 205 or the merger galaxy were companions which had contained much interstellar gas in the past. The model shows that the HI and molecular gas clouds are both stripped from the companions, and are captured by M31's gravity. The captured clouds are then rapidly accreted toward the galaxy disk along highly-tilted (polar) orbits within $\sim 10^9$ yr. The clouds, then, make a polar rotating disk in the central region, in which the clouds are further accreted toward the nucleus along spiral orbits in $\sim 10^8$ yr.

Some of the clouds would remain in the form of giant molecular clouds, as they were observed here in CO and as dark clouds. If the companion galaxies, including the possible merger galaxy, were of "primeval"-like galaxies similar to the Magellanic Clouds, the anomalously small ratios of the CO intensity and color excess to cloud mass can be explained. During accretion, the clouds could be partially heated and ionized due to friction with the ambient interstellar gas, which would produce the $\text{H}\alpha$ spiral features. However, the rest of the clouds remained at a low temperature, since no activity is present (section 2), which is required to heat up the gas to radiate strong CO emission. The accretion of massive gas clouds, and possibly the merger of a galaxy (Lauer et al. 1993), would have caused a tidal disturbance in the bulge, and disrupted the nuclear gas disk of M31. At the same time, the gravitational disturbance would have caused the central mini bar structure. Furthermore, a bar-induced accretion of interstellar gas might be somehow related to the formation of a massive black hole suggested to be present at the nucleus (Dressler, Richstone 1988; Kormendy 1988; Lauer et al. 1993).

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