Publ. Astron. Soc. Japan **41**, 113–122 (1989)

CO Observations of the Central Region of the Galaxy NGC 4258*

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(Received 1988 April 20; accepted 1988 September 21)

Abstract

The central region of the spiral galaxy NGC 4258, known for its anomalous radio arms, has been observed in the ^{12}CO ($J=1$–0) line. A massive concentration of molecular hydrogen gas was found in the center. This molecular clump is situated at the minimum of H I emission of the central H I bar and is elongated in the direction of the bar. No significant CO line was detected on the northern, denser H I bar. The high-density gas concentration and the asymmetric distribution of the H I-to-H_2 mass ratio with respect to the galaxy center may be related to the dynamical state of the gas near the nucleus. The CO rotation curve is flat even in the central few hundred parsecs. No particular association of the CO emission with the anomalous radio arms was found.

Key words: Activity of galaxies; Carbon-monoxide emission; Galaxies; Molecular clouds.

1. Introduction

The SBb-type spiral galaxy NGC 4258 is known for its anomalous arms in the radio continuum (van der Kruit et al. 1972; van Albada 1980; van Albada and van der Hulst 1982; Krause et al. 1984). The anomalous arms are interpreted as due to ejection

* Based on observations made at the Nobeyama Radio Observatory (NRO). NRO is a branch of the National Astronomical Observatory, an inter-university research institute operated by the Ministry of Education, Science, and Culture.

† On leave from the Max-Planck-Institut für Radioastronomie (October 1987–April 1988).

from the central region by a nuclear activity (van der Kruit et al. 1972; van Albada 1980; Sofue 1980; Sanders 1982), although the models are still controversial in the sense whether the arms are within the galactic plane or in the halo.

The central activity responsible for such an energetic ejection may be occurring in a dense and compact gaseous disk with high accretion rate. Therefore it may be expected that there exists a dense gaseous disk surrounding the nucleus. In fact a bar of H I gas with noncircular motion has been found in the central 1′ (van der Kruit 1974; van Albada 1980). The H I concentration toward the central region is exceptional for an Sb-type galaxy, which usually lacks H I in the center. On the other hand molecular hydrogen gas is expected to be more concentrated near the nucleus.

We have observed the central 1′×2′ area in the ^{12}CO (J=1–0) line using the Nobeyama 45-m telescope. In this paper we present the results and discuss the relation of the molecular gas with the H I bar.

2. Observations and Results

(a) Observations

The observations were made using the 45-m telescope at the Nobeyama Radio Observatory from December 20 to 26, 1987, and an additional observation was made in March 1988. The half-power beamwidth (HPBW) of the telescope at the observing frequency (115.271 GHz) was 17″, which corresponds to 540 pc at the distance of 6.6 Mpc (Burbidge et al. 1963). The aperture and main-beam efficiencies were 0.26 and 0.45, respectively. The receiver frontend was a cooled Schottky-diode-mixer receiver, and the system noise temperature (SSB) including the atmospheric effect and the antenna ohmic losses was 800 K at the zenith. The spectra were taken with the 2048-channel, wide-band acousto-optical spectrometers. The instantaneous bandwidth was 250 MHz, which provided a velocity coverage of 650 km s^{-1}. The final spectra were smoothed to a velocity resolution of 20 km s^{-1} (64 channels) in order to improve the signal-to-noise ratio. The center frequency was taken to coincide with the systemic LSR velocity of the galaxy, 457 km s^{-1} (van Albada 1980). The integration time per each point was about 24 min, which yielded the rms noise of 24 mK in the obtained spectra with a 20 km s^{-1} resolution.

A position-switching mode was used; in every cycle of the switching, one "off" (reference sky) position was observed after observing three "on" positions. The "off" position was adopted 5′ east and west, alternatively, of the center of the galaxy. The center position of the galaxy was taken at R.A. (1950) = $12^{h}16^{m}29\overset{s}{.}42$, Decl. (1950) = $47°34'53\overset{''}{.}2$ (van der Kruit et al. 1972). The pointing was calibrated by observing the SiO maser source T UMa every 1 to 2 hr. The absolute pointing accuracy was better than ±3″ (peak-to-peak ±5″). The calibration of the line intensity was made using an absorbing chopper of room temperature in front of the receiver. The intensity scale used in this paper is the antenna temperature T_A^*, corrected for the atmospheric and antenna ohmic losses but not for the beam efficiencies.

(b) Results

The observations covered the central 1′×2′ region approximately along the central

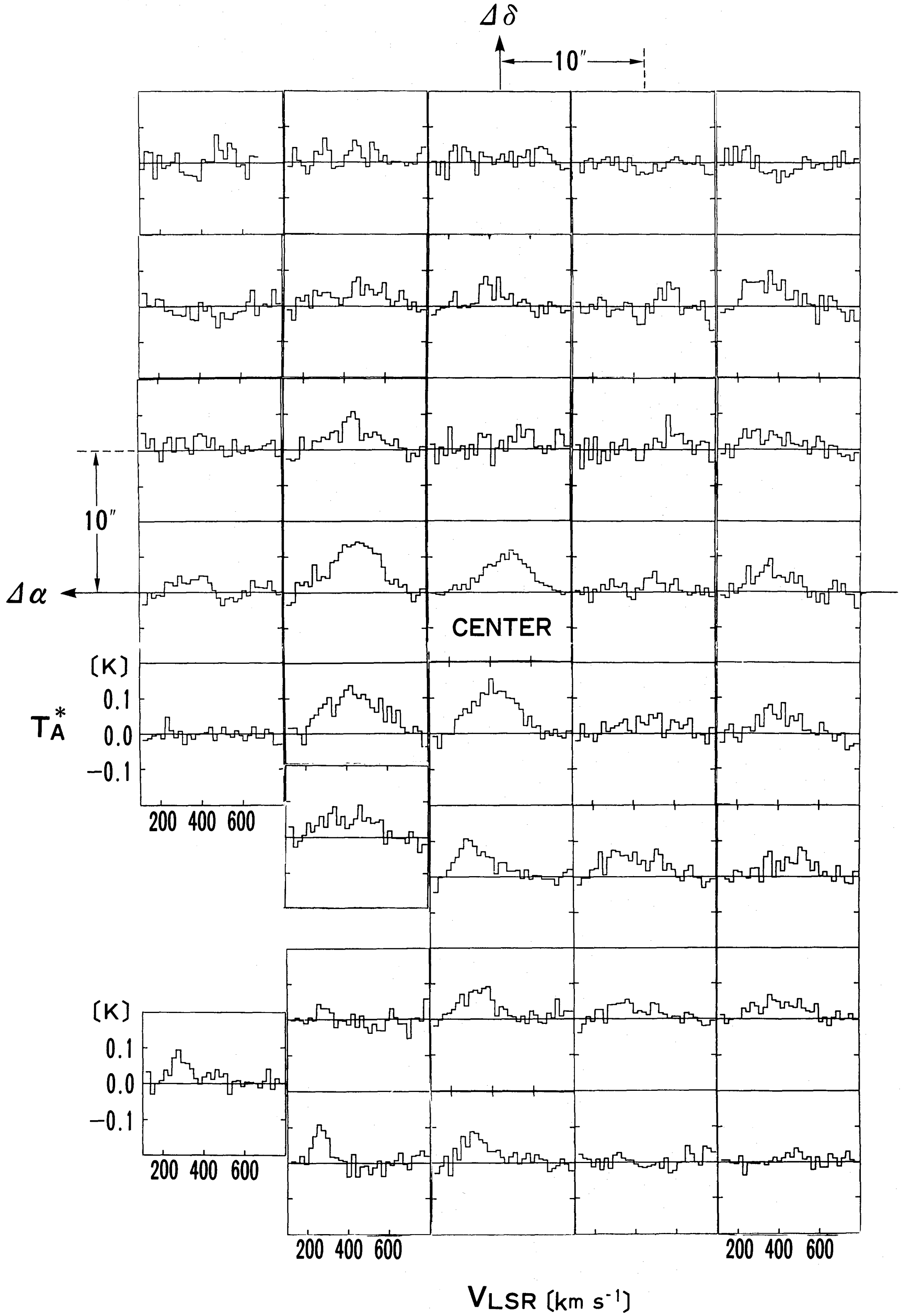

Fig. 1. Line profiles of the CO emission obtained for the central region of NGC 4258.

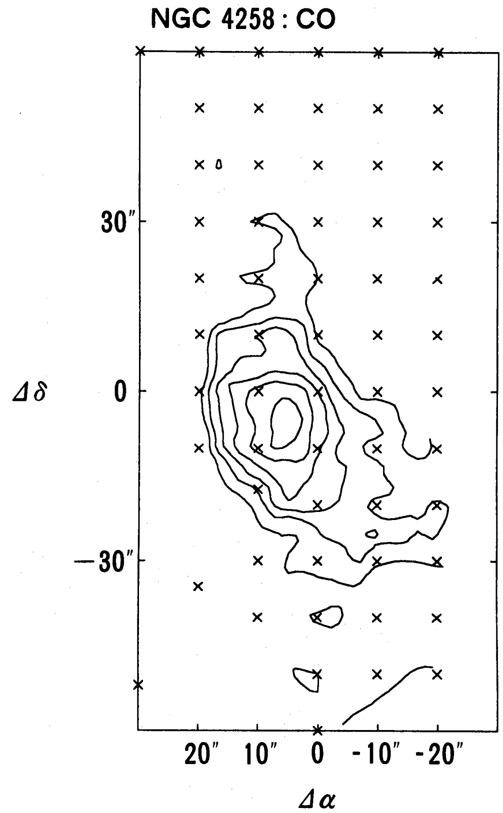

Fig. 2. Observed distribution of the CO integrated intensity. Observed positions are marked by crosses. The contour interval is $5\,\mathrm{K\,km\,s^{-1}}$ and the lowest contour is $10\,\mathrm{K\,km\,s^{-1}}$

H I bar, and the spectra were taken at every 10″ grid in the right ascension and declination directions. Spectra were also taken along the major axis for up to a distance of $\pm 3'.3$ from the nucleus, and for six points on a high-density H I clump on the northwestern spiral arm at $\Delta\alpha = -6'.5$ and $\Delta\delta = 4'.4$. The major axis and the northwestern arm were observed at 20″ interval.

The CO emission was detected only in the central region. Figure 1 shows the line profiles for the central CO emission. Figure 2 is a map of the integrated CO intensity for the observed central region. The spectra were also used to obtain position-velocity diagrams along the major axis of the galaxy and along the major axis (north-south line) of the H I bar. The diagrams are shown in figures 3a and b.

3. Discussion

(a) Distributions of the Hydrogen Gas

Intensity as high as $T_A^* \sim 0.1\,\mathrm{K}$ was recorded at positions $(\Delta\alpha, \Delta\delta) = (0'', 0'')$, $(0'', -10'')$, $(10'', 0'')$, $(10'', -10'')$. Here $\Delta\alpha$ and $\Delta\delta$ denote offset angles (on the sky) from the adopted center position in the direction of right ascension and declination, respectively. The intensity decreases rapidly in the surrounding region. The map of the integrated intensity (figure 2) shows that the high-density CO (molecular hydrogen) gas is confined in a small area of about $20'' \times 30''$ (full width) centered on $(5'', -5'')$. This clump is elongated in the direction approximately parallel to the major axis of

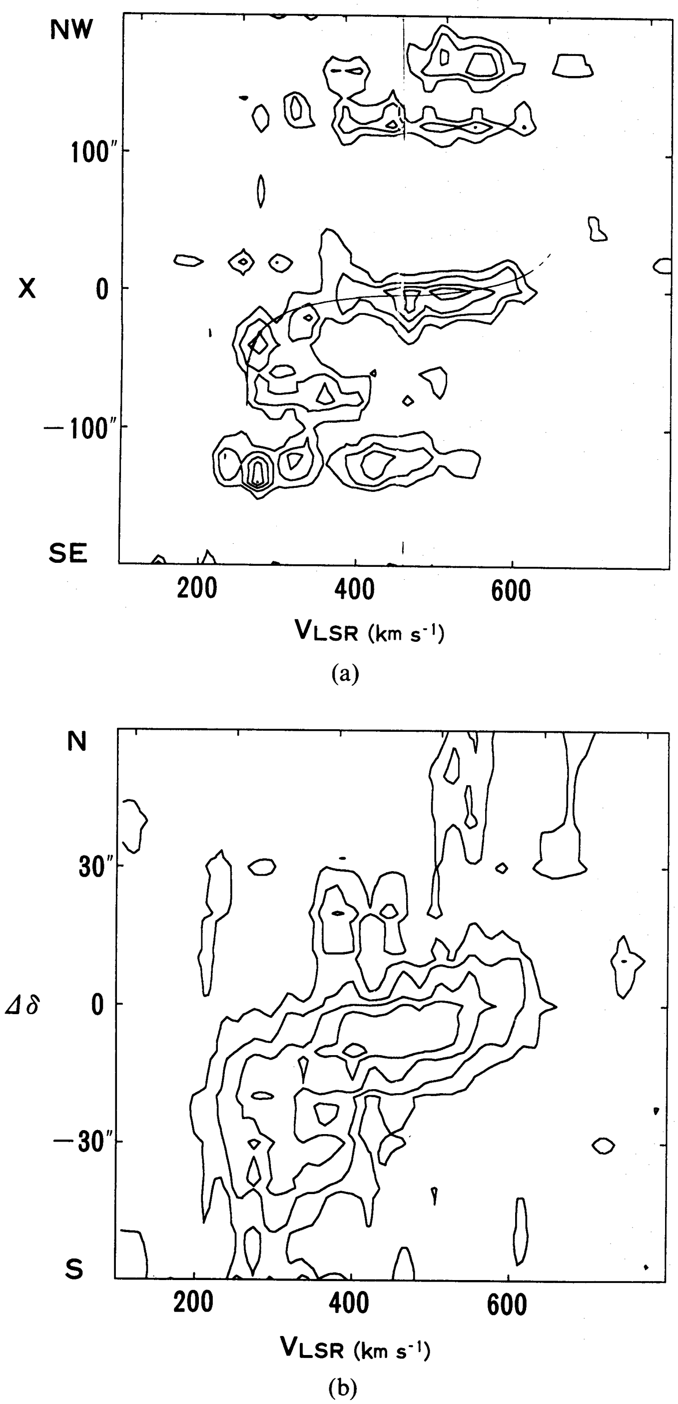

Fig. 3. (a) Position-velocity diagram of the CO emission along the major axis. The contour interval is 0.02 K T_A* and the lowest contour is at 0.04 K. The stretched features at $X=120''$ and $-120''$ are spurious due to baseline wripples: (b) Position-velocity diagram along the ridge of the H I bar, with the same contour interval as (a), but the lowest contour is at 0.02 K. Note the flat rotation in the central region of this galaxy.

the H I bar at position angle of 10° (van Albada 1980). The CO intensity toward this clump is about $35\,\mathrm{K\,km\,s^{-1}}$. The clump has the H_2 column density as high as 2×10^{22} H_2 molecules $\mathrm{cm^{-2}}$ ($=4\times10^{22}$ H atoms $\mathrm{cm^{-2}}$). If the disk thickness is several tens of parsecs, the density of the molecular hydrogen is as high as 100 H atoms $\mathrm{cm^{-3}}$.

The total H_2 mass involved in this clump is of the order of $10^8\,M_{\odot}$. This molecular hydrogen mass makes up a few percent of the total (dynamical) mass involved within 10″ (320 pc) radius of the center, $M_{\rm dyn}\sim3\times10^9\,M_{\odot}$ for a rotation velocity of $200\,\mathrm{km\,s^{-1}}$ (see section 3c). Here and hereafter we use the conversion factor from the CO intensity to the H_2 column density adopted by Young and Scoville (1982), after correcting for the difference of the antenna and beam efficiencies of the NRO 45-m and FCRAO 14-m telescopes. We adopt a conversion formula, $N(H_2)[\mathrm{cm^{-2}}]=(6\pm3)\times10^{20}I_{\rm CO}[\mathrm{K\,km\,s^{-1}}]$.

Figure 4 shows a superposition of the CO intensity map on a contour map of the H I column density and an optical photograph reproduced from van Albada (1980). The

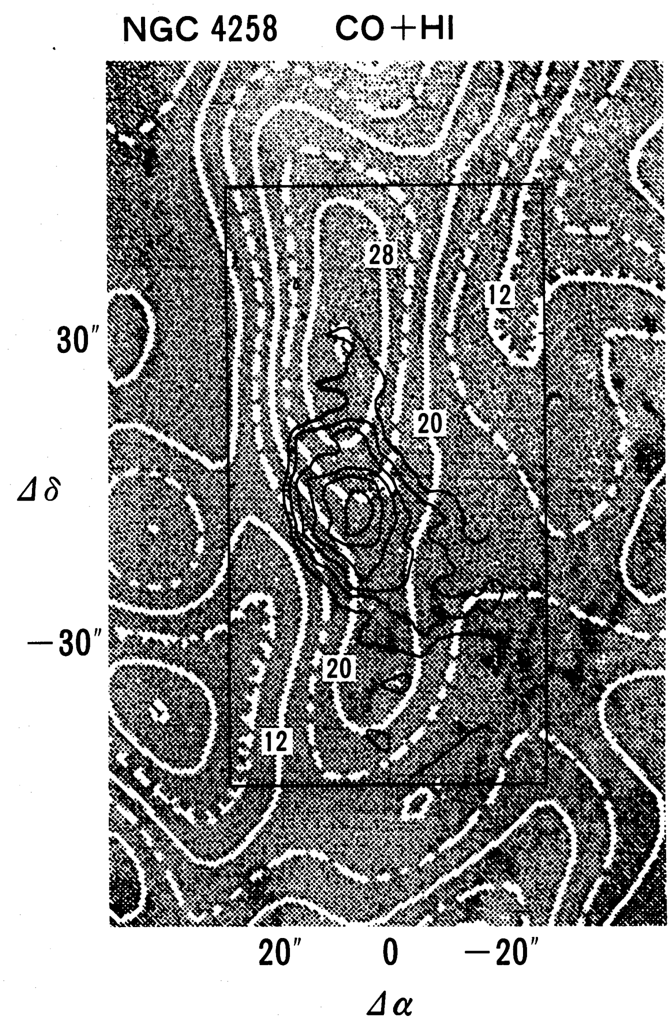

Fig. 4. CO intensity map (same as figure 2) superposed on the contour map of the H I intensity (white contours) on a background optical photograph reproduced from van Albada (1980). The H I contour unit is 10^{20} H atoms $\mathrm{cm^{-2}}$.

molecular hydrogen mass of the clump makes up a large fraction as high as 90% of the gaseous mass in the same area. The H I gas integrated on the entire bar with an extent of $30'' \times 60''$ is about 5×10^7 $M_\odot$, and the molecular hydrogen mass in the same area, excluding the CO clump, is less than 3×10^8 $M_\odot$. This leads to an atomic-to-molecular mass ratio on the entire bar greater than 0.2. The H I-to-H_2 mass ratio is about 0.05 at the clump, and 0.1 along the southern bar. On the other hand this ratio is as high as 0.3 toward the northern H I maximum on the bar. Since the H I distribution shows only slight asymmetry with respect to the center, namely $N(\mathrm{H\,I}) = 3 \times 10^{21}$ H atoms cm^{-2} in the north, while 2.2×10^{21} H atoms cm^{-2} in the south, this asymmetry must be mainly due to the asymmetry of the molecular hydrogen distribution.

It should be emphasized that the peak position of the clump is situated at the minimum emission region or near the midpoint of the peak positions of the northern and southern maxima of the H I bar: the northern bar has its maximum at $\Delta\delta = +30''$, while the southern bar has a maximum at $\Delta\delta = -35''$. This is more clearly seen in figure 5, which compares the variations of I_{CO} ($\propto N_{\mathrm{H}_2}$) and $N_{\mathrm{H\,I}}$ along the line connecting the northern and southern H I peaks of the bar and the CO peak. Although the resolution of the H I observations, $24'' \times 33''$, is not good enough to resolve the details, it is clear that the molecular clump is located where the H I has a depression on the bar.

(b) Eccentric Distribution of Molecular Hydrogen Gas

As it is readily seen from figure 2, the CO intensity distribution is significantly asymmetric with respect to the center position adopted here (van der Kruit et al. 1972). In the area surrounding the northern H I bar, the CO emission is so weak that it was not detected within our detection limit. On the other hand, in the southern bar, where the H I emission is weaker, we detected stronger CO emission.

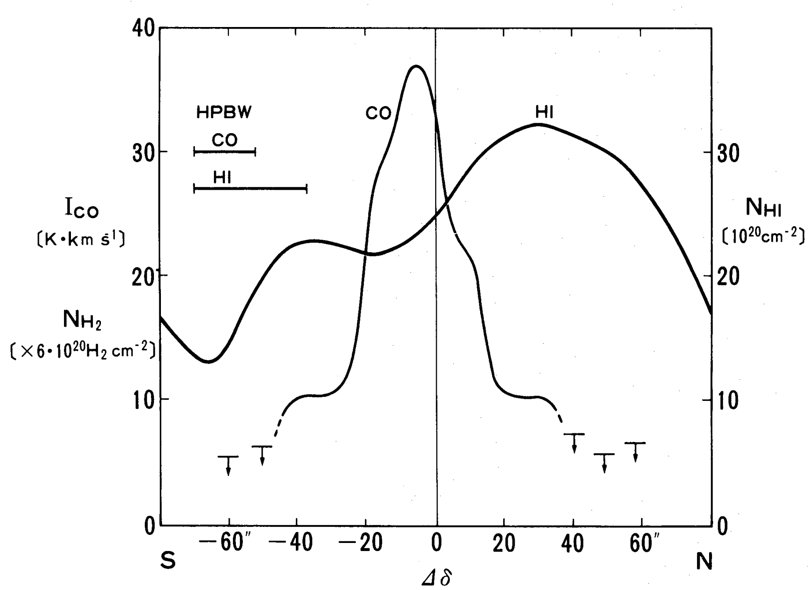

Fig. 5. Variation of the column densities of the molecular and atomic hydrogen gases along the line connecting the northern and southern H I peaks (the H I bar ridge) and the CO peak. Note that the CO maximum is located near the minimum of H I emission. Note also the significant north-south asymmetry in the molecular hydrogen distribution, and hence the atomic-to-molecular hydrogen mass ratio. The H I data are from van Albada (1980).

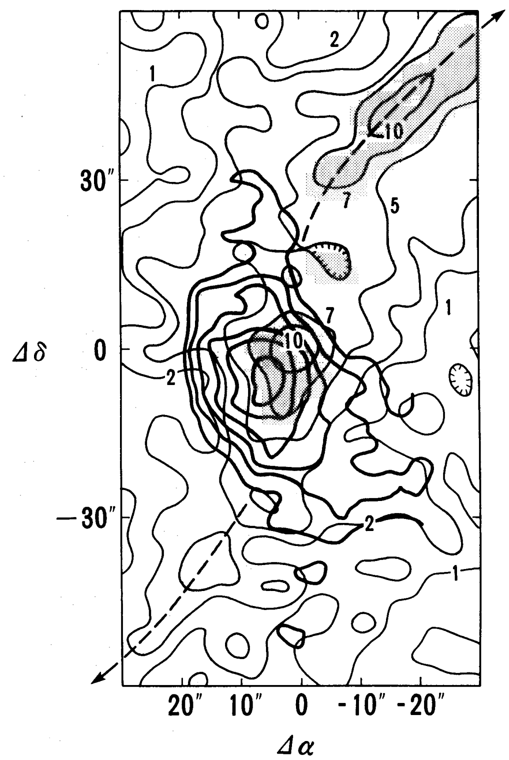

Fig. 6. The CO intensity map superposed on a radio continuum map at 1480 MHz with the resolution of 6.″5 × 6.″5 reproduced from van Albada and van der Hulst (1982). The contour unit of the radio map is 0.3 mJy/beam. Note the asymmetry of the molecular hydrogen distribution with respect to the continuum peak. Note also the asymmetry that the northwestern anomalous arm is much stronger than the southeastern arm.

Besides the molecular mass asymmetry, we note that the anomalous arms are also asymmetric: the radio continuum intensity in the northwestern arm is twice as high as that in the southeastern arm (van Albada and van der Hulst 1982). Asymmetry of the CO clump with respect to the radio continuum distribution is seen in figure 6, where the CO intensity map is superposed on a 1480-MHz continuum map of 6.″5 × 6.″5 resolution reproduced from van Albada and van der Hulst (1982). The figure shows that the CO peak is situated at 7″ southeast of the continuum peak. (There remains a possibility that the positional discrepancy between the continuum and CO peaks might be due to the systematic pointing error of the 45-m telescope. However, the amount 7″ seems too large for the error, and we here assume that the discrepancy is real.) The stronger continuum arm in the northwest seems to be ejected in the side of less dense gas. On the other hand the Hα emission associated with the anomalous arms is stronger in the southeastern region. Namely the Hα emission is stronger in the denser side of the gas distribution. The asymmetries of the radio continuum and Hα emissions may be related to the asymmetry of the mass distribution near the center; the mass ejection and propagation of the plasma beam may be affected by the mass distribution of the gas.

The present observations cover some parts of the anomalous arms. However, the signal-to-noise ratio is too poor to discuss the direct relationship of the molecular gas with the anomalous arms. At least we may state that the anomalous arms in the observed area beyond 30″ from the nucleus do not seem to be associated with the molecular gas very much.

(c) Rotation Curve

The position-velocity diagrams (figures 3a and b) can be used to derive the rotation curve in the innermost region of $|X|<1'$. Here X denotes the distance from the center along the major axis. In figure 3a we may trace the maximum positions of CO emission as indicated by the full line. A similar but somewhat better trace is also possible in figure 3b. The maximum positions of the CO intensity are consistent with those expected from a flat rotation curve with a slight increase near the center. Taking the inclination angle of $i=72°$ (van Albada 1980), we obtain an almost constant velocity, $V_{rot}\simeq 200\,\mathrm{km\,s^{-1}}$.

Contrary to the flat rotation obtained from the molecular gas, the H I rotation is more rigid at $|X|<2$ kpc (van Albada 1980). The H I rotation velocity attains a maximum of 270 km s^{-1} at $|X|=2$ kpc, and decreases gradually, approaching a constant velocity of 210 km s^{-1}. This discrepancy between the molecular and atomic rotation curves may be due to a wider beam size, $24''\times 33''$, of the H I observations. The CO rotation may be a manifestation of the true rotation of the inner region of the galaxy. On the other hand, the Hα rotation curve (van der Kruit 1972) also shows a different behavior both from the molecular and atomic gases. It is rather rigid at $|X|=$ 0–50″, attains a maximum velocity of 270 km s^{-1} at $|X|\sim 70''$, and decreases gradually approaching a constant rotation of 200 km s^{-1}. The peculiar behavior of the Hα velocity could be due to high noncircular motion of the ionized gas (van der Kruit 1974).

(d) High Velocity Dispersion

The apparent displacement of the dynamical center in figure 3 may be attributable to the eccentric location of the CO clump. Besides the rotation effect the high velocity dispersion may also be due to high internal motion and a dynamical state of gas as a consequence of the rapid accretion (contraction) by a galactic shock wave in a barred potential (e.g., Sørensen et al. 1976; Roberts et al. 1979). Some ejection and/or expansion caused by the activity of the nucleus (van der Kruit 1972; Sofue 1980; Sanders 1982) may also result in a high velocity dispersion. From his Hα observations van der Kruit (1974) reported high noncircular motion near the nucleus. At distances more than 20″ from the center the CO gas is rather quiet and seems to exhibit normal rotation (figures 3a and b).

(e) Spiral Arm

H I observations show patchy gaseous arms 7′ northwest of the center (van Albada 1980). The highest H I emission, $N(\mathrm{H\,I})=4\times 10^{21}\,\mathrm{cm^{-2}}$, is observed toward the northwestern arm at R.A. $=12^{h}15^{m}57^{s}.0$, Decl. $=47°39'33''.2$, or $\Delta\alpha=-328''$, $\Delta\delta=285''$ with respect to the center position. We obtained six spectra around this position. However, no significant emission was recorded at any point. An upper limit to the H_2 column density, $\approx 2\times 10^{21}$ H_2 molecules $\mathrm{cm^{-2}}$, gives the H I-to-H_2 mass ratio greater than unity toward this H I maximum.

The authors are indebted to the Ministry of Education, Science, and Culture for the financial support under Grant No. 61460009 (Y. Sofue, 1986–1988).

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