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CO Observations of the Peculiar Galaxy NGC 7625 and Detection of Infalling Molecular Gas

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Abstract

We have carried out ^{12}CO ($J = 1 - 0$) emission-line observations of NGC 7625 (=Arp 212) with the Nobeyama 45-m telescope. We have found that the molecular gas is widely spread in the galaxy, and is correlated with visible dust lanes; its molecular mass is at least $1.54 \times 10^9\ M_\odot$. The velocity of molecular gas is not fully consistent with the rotation of the stellar disk. Part of the molecular gas, corresponding to a prominent dark lane, shows a redshifted velocity with respect to the stellar disk, suggesting an infall of the molecular gas onto the stellar disk. We have estimated the present-day and past ($\simeq 10^9$ yr ago) star formation rates using the far-infrared and B luminosities, respectively, and have found that these two star formation rates have the same value, as large as $8.5\,M_\odot\ \mathrm{yr}^{-1}$. This suggests that a constant star formation rate has been maintained for the last 10^9 yr in this galaxy. In order to explain this high star formation rate and the velocity anomaly of CO gas, we suggest that molecular gas has been infalling onto this galaxy at a constant rate, thus enhancing star formation.

Key words: CO emission — Dust lanes — Galaxies — Molecular hydrogen — Star formation

1. Introduction

We know that, in general, the later is the galaxy type, the more gas it contains. Since there is always an exception to any rule, some types of early-type galaxies have the same amount of gas as that in late-type galaxies. Since dust lanes are supposed to be accompanied by gas, if we find dust lanes in a galaxy there may be a certain amount of gas in that galaxy. As an extreme case there are some elliptical galaxies in which dust lanes are visible on their optical images, which are called Dust-Lane Ellipticals (Hawarden et al. 1981; Ebneter and Balick 1985; Sadler and Gerhard 1985). Dust-Lane Ellipticals are classified into mainly three types according to their dust lanes' optical morphology: oblate type, in which the dust lane is parallel to the galaxy's major axis; prolate, in which the dust lane is parallel to the galaxy's minor axis; and skew, in which the dust lane is linear, but not parallel, to the galaxy's either axes. Among them there are galaxies which show chaotic or pacthy morphological dust lanes. As a good example of such objects we have chosen NGC 7625 (=UGC 12529=VV 280). From IRAS and CO-line observations it is known that this galaxy has star forming activity (Young et al. 1986). A detailed study of this galaxy is thus useful for studying the origin of dust lanes in early-type galaxies as well as the relation between the dust lane and star forming activity.

NGC 7625 is one of the galaxies cataloged in *Atlas of Peculiar Galaxies* (Arp 1966) and is named Arp 212. According to RC2 (de Vaucouleurs et al. 1976) NGC 7625 is classified as SA(rs)a, pec. This galaxy has a few outstanding dust lanes in optical photograph, which implies the existence of a significant amount of gas. Blue light (λ=430.0 nm), red light (λ=678.2 nm) and Hα (λ=660.7 nm) observations (Lynds and Furenlid 1973) have revealed several bright H II regions in the north-

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Table 1. Basic parametrs of NGC 7625.

Quantity	Symbol	Value	Reference
Right ascension*	$\alpha(1950)$	$23^{h}18^{m}00^{s}.6$	Dressel and Condon (1976)
Declination*	$\delta(1950)$	$+16°57'15''$	Dressel and Condon (1976)
Morphology		SA(rs)a,pec	RC2
Size		$1'.5 \times 1'.5$	UGC
Major axis	P.A.	26°	Demoulin (1969)
Inclination	i	21°	RC2
Heliocentric velocity	$V_{\rm H.C.}$	1620 km s^{-1}	Demoulin (1969)
Blue magnitude	B_T^0	12.47	RC2
Color index	$(B-V)_T^0$	0.61	RC2
Distance	D	23.7 Mpc	this paper
H I-line integral	$\int S_{\rm H\ I} dv$	18.5 Jy km s^{-1}	Knapp et al. (1978)
FIR flux	$S_{60\mu m}$	9.0 Jy	*IRAS* PSC (1985)
	$S_{100\mu m}$	18.3 Jy	*IRAS* PSC (1985)
Total mass	$M_{\rm T}$	3–8 × 10^{10} $M_{\odot}$	Balkowski et al. (1972)
			Peterson and Shostak (1974)

* Reference center position No. 3 (0″, 0″) in table 2.

western side of the nucleus, and a heavier reddening of the central region, compared to the surrounding region. Spectral observations (Demoulin 1969) showed that its spectrum is of an early type: Balmer absorption lines from Hβ to H12, and emission lines as Hα, [N II], [S II], [O II], [O III], which are usually found in earlier-type spiral galaxies, are intense. The central 3.5 kpc region shows rigid rotation around the minor axis.

Many 21-cm neutral hydrogen-line studies have been carried out for this galaxy with the Arecibo 305-m telescope, the Green Bank 91-m telescope, etc. (Balkowski et al. 1972; Peterson and Shostak 1974; Knapp et al. 1978). These observations have shown that the H I content of this galaxy is comparable to that in our Galaxy. CO-line observations have been made with the FCRAO 14-m telescope (Young et al. 1986; Thronson et al. 1989), and a significant amount of molecular gas has been detected. However, the HPBW(=45″) was not sufficient investigating the distribution and kinematics of molecular gas, which is regarded as being the most useful tracer of dust lanes. Radio continuum observations at 2380 MHz have been made with the Arecibo telescope (Dressel and Condon 1978) and 4.9 GHz observations with the VLA (Wrobel and Heeschien 1988; Gregorini et al. 1989). The radio-emitting regions are confined to within 30″ in diameter, corresponding to 3.5 kpc, although their morphology is complex. Further, it is remarkable that the radio nucleus is displaced to the southeast by 14″ of the optical one (Dressel and Condon 1976).

Basic data concerning NGC 7625 compiled from the literature are given in table 1, where the galaxy's inclination was calculated by $i = \arccos(1/R_{25})$ and the distance by $D = V_{\rm G.C.}/H_0$; here, $V_{\rm G.C.}$ is the galacto-centric velocity derived from $V_{\rm H.C.}$, and H_0=75 km s^{-1} $\rm Mpc^{-1}$.

2. Observations and Results

The observations were made on 1990 January 20 and 25, and 1991 May 17, 18 and 20, using the 45-m telescope at the Nobeyama Radio Observatory in an observational program of a CO Survey of Arp's Peculiar Galaxies. The HPBW and the main-beam efficiency of the antenna at 115 GHz were 15″ and 0.45, respectively. The pointing was checked by using the SiO maser source R Peg; the accuracy was better than 5″.

The receiver was a cooled Schottky barrier diode receiver combined with a 2048-channel acousto-optical spectrometer. The bandwidth was 250 MHz, covering a velocity range of 650 km s^{-1}. The frequency resolution was 250 kHz, corresponding to a velocity resolution of 0.65 km s^{-1}. In order to improve the signal-to-noise ratios, we binded every 96 channels. The final velocity resolution was 30 km s^{-1}. The system noise temperature, including atmospheric effects, was about 800 K.

The observed positions are shown in figure 1. The observations were made for a total of 9 positions with a position-switching mode. The interval of the grid was taken to be 15″. The reference positions were taken at offsets of ±5′ from the galaxy center in right ascension. The beam size, 15″, corresponds to 1.7 kpc at a distance 23.7 Mpc of the galaxy.

Figure 2 shows the obtained CO spectra for NGC 7625. Table 2 shows the observed CO intensities, mean LSR velocities, and derived H_2 masses within the beam. Here, the integrated CO intensity is defined by

$$I_{\rm CO}({\rm K\ km\ s^{-1}}) = \int T_{\rm A}^{*}({\rm K})dv({\rm km\ s^{-1}})\eta_{\rm B}^{-1}, \quad (1)$$

where $\eta_{\rm B}$ is the main beam efficiency of the telescope; $\eta_{\rm B} = 0.45$. The mass of molecular gas, $M_{\rm H_2}$, was estimated by the relation (Scoville et al. 1987)

$$M_{\rm H_2}(M_{\odot}) = 5.8 \times 10^{6} I_{\rm CO}({\rm K\ km\ s^{-1}})A({\rm kpc^2}), \quad (2)$$

where A is the projected area corresponding to HPBW at the distance of the galaxy. Here, since HPBW=15″ so we obtain A=2.33 kpc^2. In table 2, for reference, we also show the result of Thronson et al. (1989) who used the FCRAO 14-m telescope (HPBW=45″). For the result of Thronson et al. (1989), we used $\int T_{\rm A}^{*}dv$=5.7 (K km s^{-1}), $\eta_{\rm B} = 0.69$ and A=21.0 kpc^2 for HPBW=45″. We note that our observations covered the area observed with the 14-m FCRAO telescope, and that both data are consistent with each other, as described in the next section.

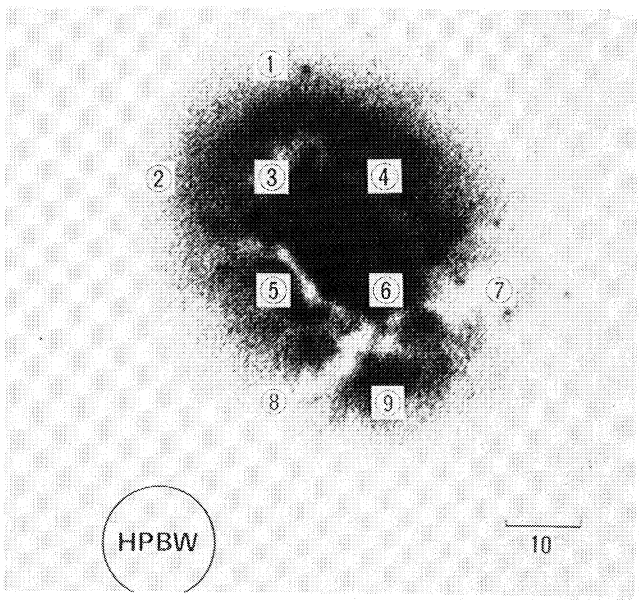

Fig. 1. Photograph of NGC 7625 reproduced from Arp's (1966) *Atlas of Peculiar Galaxies* together with the observed positions. The beam size (15″) is shown by the open circle. Top is north, left is east.

3. Discussion

3.1. *Total Amount and Distribution of Molecular Gas*

We compare the distribution of molecular gas with the observations by Thronson et al. (1989). Observed positions No. 1–6 are included within their 45″ beam, and the sum of the molecular masses at these positions ($11.0 \times 10^8 M_{\odot}$) is roughly the same as the molecular mass derived by their observation ($10.1 \times 10^8 M_{\odot}$). However, the CO emission is strongest at position No. 6, and next at No. 3; there is no emission at No. 1. We can conclude that in Thronson et al.'s (1989) beam the CO emission is stronger at the southwestern side. Strong CO emission toward position No. 6 must be caused by a large peculiar dust lane, which can be easily seen on the optical photograph (figure 1), because CO emissions are strong toward a peculiar dust lane and dust is supposed to be accompanied by molecular gas.

We estimate the mass of molecular gas contained within NGC 7625 from the results obtained here. When we sum up the mass of molecular gas for all of the observed positions, we obtain $M_{\rm H_2} = 1.54 \times 10^9 M_{\odot}$. Since the observed positions do not completely cover the galaxy and the molecular gas is not confined within any limited region, there must exist larger amount of molecular gas.

The total mass of the H I gas is derived using the relation

Table 2. Observed results.

Position	$I_{\rm CO}$ (K km s^{-1})	$V_{\rm mean}$ (km s^{-1})	Area (kpc^2)	$M_{\rm H_2}$ ($M_{\odot}$)
No. 1 (0″, +15″)	$< 6.0^*$	...	2.33	$< 0.8 \times 10^8$
No. 2 (+15″, 0″)	9.3±4.7	1710	2.33	$(1.3 \pm 0.6) \times 10^8$
No. 3 (0″, 0″)	19.8±8.9	1650	2.33	$(2.7 \pm 1.2) \times 10^8$
No. 4 (−15″, 0″)	15.1±6.9	1580	2.33	$(2.0 \pm 0.9) \times 10^8$
No. 5 (0″, −15″)	10.9±3.3	1560	2.33	$(1.5 \pm 0.4) \times 10^8$
No. 6 (−15″, −15″)	26.2±5.3	1620	2.33	$(3.5 \pm 0.7) \times 10^8$
No. 7 (−30″, −15″)	16.0±5.8	1650	2.33	$(2.2 \pm 0.8) \times 10^8$
No. 8 (0″, −30″)	7.1±3.6	1580	2.33	$(1.0 \pm 0.5) \times 10^8$
No. 9 (−15″, −30″)	9.1±3.6	1590	2.33	$(1.2 \pm 0.5) \times 10^8$
Thronson et al. (1989)	8.3	1630	21.0	10.1×10^8

* A velocity width of 150 km s^{-1} is assumed.

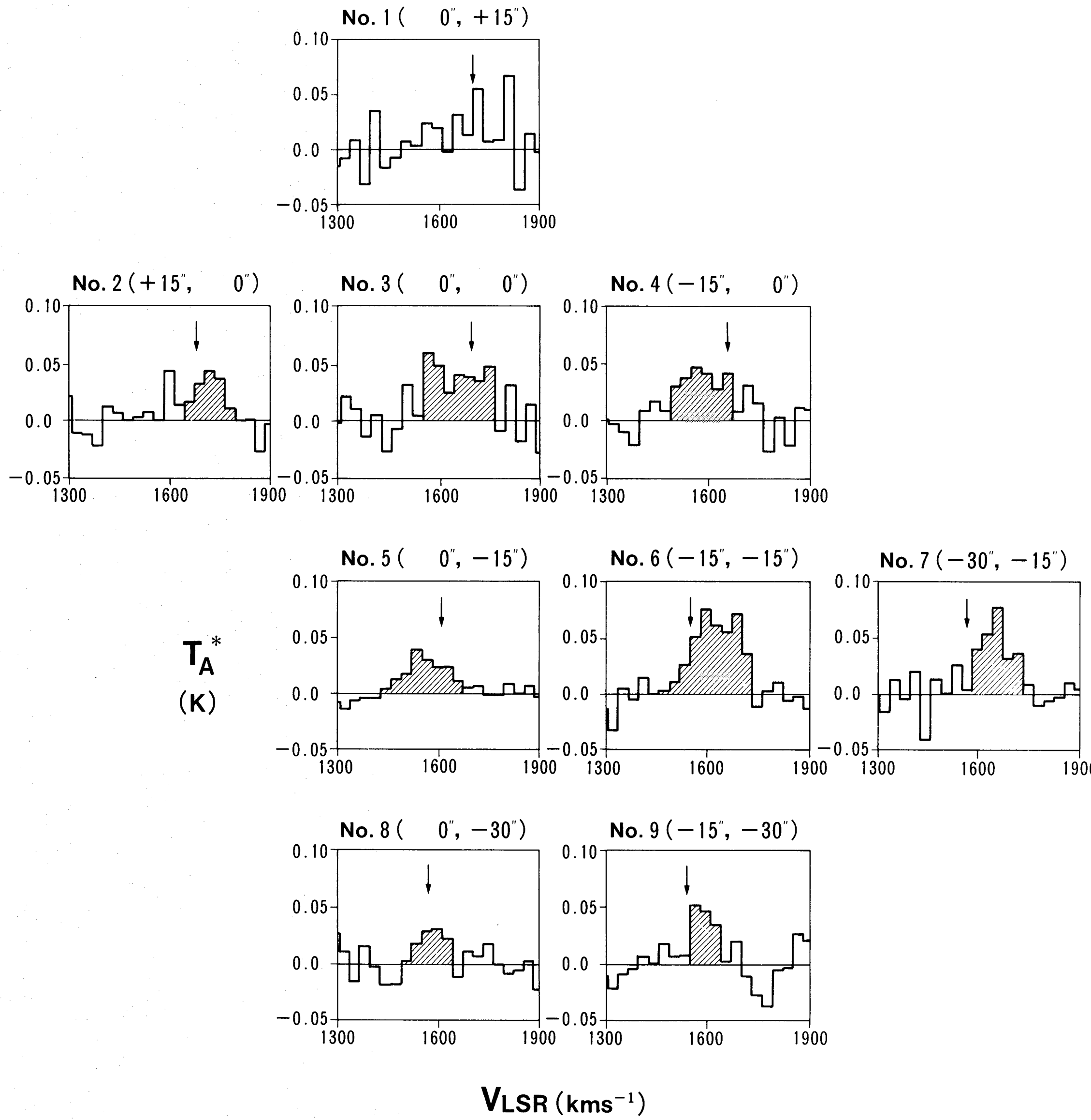

Fig. 2. ^{12}CO (J=1–0) line profiles for NGC 7625 with a velocity resolution of ΔV=30 km s^{-1} are shown for the nine observed positions. The arrows indicate the calculated $V_{\rm LSR}$ from a simple rotation curve based on optical observations (see text).

$$M_{\rm H\,I}(M_\odot) = 2.36\times10^5 D^2({\rm Mpc})\int S_{\rm H\,I}dv({\rm Jy\ km\ s^{-1}}); \qquad (3)$$

we obtain $M_{\rm H\,I} = 2.45\times10^9\ M_\odot$ using the H I data by Knapp et al. (1978). The total gas mass ($M_{\rm H_2}+M_{\rm H\,I}$) amounts to 5–10% or more of the total mass of the galaxy (3–8$\times10^{10} M_\odot$; Balkowski et al. 1972; Peterson and Shostak 1974).

3.2. *Velocity Anomaly of Molecular Clouds—Infalling Gas?*

The velocities of CO gas toward NGC 7625 do not seem to be fully consistent with the rotation of the galaxy studied by optical observations. Optical observations (Demoulin 1969; Y. Taniguchi 1990, private communication) show that both the Hα and [N II] emissions, which come from ionized gas, and Ca II absorption, which comes from underlying stars, indicate rigid rotation within the central 10$''$ radius region.

Since our observed positions do not exactly align with Demoulin's (1969) observed slit positions, we cannot directly compare the optical velocities with our CO gas velocities. According to optical observations, the stellar disk within 10$''$(=1.1 kpc) from the optical center shows a rigid rotation with the projected velocity gradient, 8.0 km s^{-1} arcsec^{-1}; in the outer region the projected velocity is constant at 80 km s^{-1}. This corresponds to a true rotation velocity of 220 km s^{-1} for an inclination of 21° (table 1). From this observation we can calculate the expected velocities at our observed positions. The expected optical velocities are indicated by the arrows in figure 2. Though Demoulin (1969) does not mention where in the galaxy she put slits, we assumed here that the dynamical center of this galaxy coincides with the optical nucleus, which we read from surface photometry data by Gregorini et al. (1989), and circular symmetry. [Note that the reference center position (No. 3) of our observations is shifted by $0^{s}\!.6$ to the east and 8″ to the north from this nucleus position.]

Regarding positions Nos. 2, 3, 5, 8, and 9, the optical and CO velocities coincide with each other within the velocity error mentioned below. As mentioned later, faint dark clouds, which are part of the ring-like dust lane, are seen toward Nos. 3 and 5. This indicates that this galaxy has a molecular gas ring whose radius is about 1 kpc, which coincides with the turnover point of the rotation curve.

However, on positions Nos. 4, 6, and 7, the optical and CO velocities do not agree with each other by 70–80 km s^{-1}. On positions Nos. 4 and 6 the edges of CO emission profiles are seen at the optical velocities. This may be emission from a ring-like dust lane, as described previously regarding Nos. 3 and 5. Although there are some sources of velocity errors, they are not responsible for the optical and CO velocity discrepancy, according to the following. A telescope pointing error of ±5″ would cause a velocity error of ±30 km s^{-1}, ±25 km s^{-1}, and ±12 km s^{-1} for Nos. 4, 6, and 7, respectively. Thus, the pointing error cannot explain this velocity discrepancy. Another possible error is a dispersion of 40–50 km s^{-1} of the optical velocities of Demoulin (1969). Part of this discrepancy, however, may be caused by an error in the optical spectroscopic observation; at other positions the stellar and gaseous velocities show good agreement. We thus conclude that the velocity field model used here is sufficiently good to make a comparison of the stellar and gaseous velocities. In addition, even if we took 37°, derived from inner dust lane ring, for the galaxy's inclination angle, the expected velocities would change by only ±5 km s^{-1} at maximum.

Faint dark clouds are seen toward positions Nos. 3, 4, 5, and 6 in the optical photograph (cf. Arp 1966; see figure 1). These dark clouds make a ring centered on the optical nucleus. We can see a large peculiar dust lane on positions Nos. 6, 7, and 8 where the obscuration is much heavier than that on other positions. This prominent dust lane looks like a straight line, being almost parallel to the minor axis of the galaxy; these positions are in a region where the stellar rotation approaches a constant velocity from optical observation, which results in differential rotation. This almost straight dust lane cannot be maintained in a differentially rotating disk, since such rotation would change the shape of the dust lane into an arc-like morphology. This fact thus indicates that the dark lane is not rotating differentially together with the stellar system, but that it lies in front of the galactic disk being silouhetted against the stellar disk and is observed as a strong CO emitting region toward Nos. 6 and 7. The CO velocity on No. 4 is blueshifted and that on Nos. 6 and 7 is redshifted with respect to the optical velocity.

This dust lanes' optical morphology and velocity anomaly suggest that CO gas detected toward No. 4 is behind the stellar disk and is infalling toward the galaxy from behind and CO gas on Nos. 6 and 7 is connected with the peculiar dust lane and is infalling toward the galaxy.

3.3. Star Formation

In this section, we discuss star formation history in NGC 7625, comparing the present-day and past ($\simeq 10^9$ yr ago) star formation rates.

We first estimate the present-day star formation rate using the far-infrared luminosity. The infrared luminosity at 42.5–122.5 μm is $L_{\rm IR} = 1.3 \times 10^{10}\ L_{\odot}$, which is derived from the IRAS data by using the relation

$$L_{\rm IR}(L_{\odot}) = 5.6 \times 10^5 D^2({\rm Mpc})[2.58 F_{60\mu{\rm m}}({\rm Jy}) + F_{100\mu{\rm m}}({\rm Jy})] \tag{4}$$

(Lonsdale et al. 1985). Then the present-day star formation rate is estimated from a formula by Thronson and Telesco (1986),

$$\dot{M}_{\rm SF,IR}(M_{\odot}\ {\rm yr}^{-1}) = 6.5 \times 10^{-10} L_{\rm IR}(L_{\odot}), \tag{5}$$

with the assumption that all of the infrared radiation is emitted from the dust around very young stars (born within 2×10^6 yr) and that Salpeter's IMF has a slope index of 2.35. We thus estimate the present-day star formation rate to be $\dot{M}_{\rm SF,IR} = 8.5\ M_{\odot}\ {\rm yr}^{-1}$ for NGC 7625. Since this rate is an upper limit for the assumption that all the infrared radiation comes from star forming regions, so it might be smaller in practice (Thronson et al. 1989). Since this rate is close to the rate of starburst galaxies by Bushouse (1987), star formation in NGC 7625 appears to be active.

We next estimate the past star formation rate using the B-band luminosity. The B-band luminosity of this galaxy is $L_B = 1.3 \times 10^9\ L_{\odot}$, derived from the total B magnitude (B_T^0) and the distance (table 1). With an assumption that all blue-light photons come from young stars (born within 10^9 yr) of the main sequence, the past star formation rate can be estimated using the formula by Thronson and Telesco (1986),

$$\dot{M}_{{\rm SF},B}(M_{\odot}\ {\rm yr}^{-1}) = 6.5 \times 10^{-9} L_B(L_{\odot}); \tag{6}$$

we obtain $\dot{M}_{\mathrm{SF},B} = 8.5\,M_{\odot}\ \mathrm{yr}^{-1}$ for NGC 7625. This rate is also an upper limit and the same slope index of IMF as for $\dot{M}_{\mathrm{SF,IR}}$ (2.35) is assumed.

The fact that the present star formation rate has the same value as that for the past 10^9 yr implies that star formation activity has been maintained for the last 10^9 yr at this high rate.

In order to maintain the observed star formation activity during the last billion years, some supply source of molecular gas is required. One possibility is the mass of stars returning to interstellar space by mass-loss process of evolved stars. This return rate can be calculated by Faber and Gallagher (1976) as follows:

$$\dot{M}_{\mathrm{rtn}}(M_{\odot}\ \mathrm{yr}^{-1}) = 10^{-10} L_B(L_{\odot}), \tag{7}$$

and $\dot{M}_{\mathrm{rtn}} = 0.11\,M_{\odot}\ \mathrm{yr}^{-1}$ in NGC 7625. This relation also assumes a slope index 2.35 of IMF. As a result, the total mass returning to interstellar gas is $1.1\times 10^8\,M_{\odot}$ in 10^9 yr. This is negligible compared to the mass used for star formation, and cannot be sufficient to supply the fuel required for the star formation in this galaxy.

Another possibility is that there was a sufficient amount ($\simeq 10^{10}\,M_{\odot}$) of molecular gas 10^9 yr ago, and that the gas has been consumed to gradually form stars at a constant rate. If this is the case, the galaxy must have been extremely gas rich (30–40% in gas) a billion years ago. However, the velocity anomaly cannot be explained.

An alternative possibility is that the fuel came from outside of the disk. We suggest that molecular clouds having a velocity anomaly, as observed toward positions Nos. 4, 6, and 7, could be part of such an accreting gas system. Namely, the relatively high rate of star formation has been maintained for the past billion years by an almost constant supply of gas clouds from an intergalactic gas system surrounding this galaxy. Suppose that the extent of molecular cloud toward Nos. 6 and 7 is the length of the peculiar dust lane, namely ~ 3 kpc. The mass of that cloud is $5.7\times 10^8\,M_{\odot}$ and the observed anomalous velocity is ~ 75 km s^{-1}. Then, the accretion rate of an intergalactic cloud would be $\sim 15\,M_{\odot}\ \mathrm{yr}^{-1}$. This value is larger than, but enough, to explain the previously derived star formation rate ($\sim 8.5\,M_{\odot}\ \mathrm{yr}^{-1}$). Although the inclination angle of the galaxy derived from the isophotal axitial ratio (R_{25}) is 21° (RC2 1976), which must represent the galaxy's overall dynamical system, that of the ring-like dust lane derived from its morphology is 37° (Demoulin 1969). If the dust lane has an internal origin, it must have been rotating in the same way as a stellar system for about 10^{10} yr, and its orbital plane would coincide with the stellar disk. This discrepancy of the inclination angles shows that the dust lane and stars are not rotating in the same plane. If the molecular gas infalling onto the galaxy is the origin of the dust lane, namely, the dust lane has an external origin, this discrepancy may occur.

Note added in proof: Dr. M.-H. Ulrich has kindly sent us a new optical rotation curve. Using the new data we confirmed the systematic difference between the optical and CO velocities. However, the sense of velocity difference is opposite to that described in section 3.2: CO velocities are blueshifted in the SW side by about 100 to 200 km s^{-1}. We could interpret this fact as due either to (a) ejection of molecular gas from the disk by starburst activity, or to (b) infall from the other side being observed after penetrating the disk as discussed in this paper. Calculated new optical LSR velocities at our observing points are as follows: 1600 km s^{-1} at point No. 1; 1616 at No. 2; 1604 at No. 3; 1628 at No. 4; 1669 at No. 5; 1746 at No. 6; 1717 at No. 7; 1714 at No. 8; and 1744 km s^{-1} at No. 9.

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