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CO EMISSION FROM THE POLAR-RING S0 GALAXY NGC 2685 AND ORIGIN OF THE RING STRUCTURE

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ABSTRACT

The ^{12}CO($J = 1$–0) emission line has been detected in the prototype polar-ring S0 galaxy NGC 2685 (= UGC 4666 = Arp 336). The central 820 pc region of NGC 2685 contains molecular gas of a mass of $7 \times 10^7 \mathscr{M}_\odot$. The observed CO emission profile shows a flat-top feature, suggesting that the molecular clouds are distributed either in a disk or in a ringlike region. Comparing kinematical properties of CO gas with that of H I gas, we consider that the circumnuclear CO gas has been fed from the helix structure. Since the nuclear ionized region shows a LINER-like excitation, the molecular gas detected by us may have little relation to the star-forming activity in this galaxy. In fact, the star-formation efficiency estimated from the ratio of $L_{\rm FIR}/\mathscr{M}_{\rm H_2}$ is significantly lower than those of isolated spiral and interacting/merging galaxies. As a formation mechanism of the helix and the faint outer ring of NGC 2685, we suggest a possibility of interaction with a distant partner UGC 4683. The distance between NGC 2685 and UGC 4683 suggests that the age of the helix and the outer ring may be more than 10^9 yr. Such a long time interval is favorable to the formation of the ring structures. If this is the case, the molecular gas has been accumulated toward the central 820 pc region of the galaxy in the same period. The accretion rate is estimated to be an order of 0.01 $\mathscr{M}_\odot$ yr^{-1}.

I. INTRODUCTION

Early-type (E and S0) galaxies are observed as gas-poor systems. However, in some early-type galaxies, evidence for abundant gaseous contents has been obtained by H I observations (Knapp, Turner, and Cunniffe 1985; Wardle and Knapp 1986), dust-lane features (Ebneter and Balick 1985), and x-ray observations (Forman, Jones, and Tucker 1985). There is still a controversy between internal or external origin of gases in such galaxies (cf. Faber and Gallagher 1976). In order to understand the star-forming history in early-type galaxies, it is necessary to study present-day abundance of cold molecular gas. Recently, several attempts have been made to search for the CO emission in early-type galaxies such as S0 galaxies (Sage and Wrobel 1989; Thronson *et al.* 1989; Wiklind and Henkel 1989). Further, Taniguchi, Kameya, and Nakai (1989, 1990) detected the CO emission in two S0 galaxies with starburst nuclei. Although, up to now, about 20 early-type galaxies have been detected in CO, it is difficult to deduce general properties of star-forming history in these galaxies.

During the course of a CO survey for Arp's (1966) peculiar galaxies (Sofue *et al.* 1990), we have detected CO ($J = 1$–0) emission in a peculiar S0 galaxy NGC 2685 (= UGC 4666 = Arp 336) using the 45 m radio telescope of the Nobeyama Radio Observatory (HPBW = 15 arcsec), while previous attempts by several authors resulted in negative CO detection in this galaxy (Rowan-Robinson, Phillips, and White 1980; Johnson and Gottesman 1980; Thronson *et al.* 1989). NGC 2685 is known to be a peculiar galaxy because it has a *helix* structure surrounding a S0 (or spindle) galaxy (Sandage 1961; Arp 1966). In addition, a faint outer ring is present nearly in the plane of the S0 main body. The helix structure is usually considered as a prototype of polar ring structure, and more than a dozen of polar-ring galaxies have been collected in the literature (Schweizer, Whitmore, and Rubin 1983; Wakamatsu and Arp 1983; Taniguchi, Shibata, and Wakamatsu 1986). The origin of polar ring structure may be due to an accretion event (cf. Toomre 1977; Shane 1980; Schweizer, Whitmore, and Rubin 1983). Therefore, NGC 2685 provides a chance to study the star-forming activity triggered by external accretion of cold gases into a galaxy.

In this paper, we report the first detection of CO emission in the central 15 arcsec region of NGC 2685 and discuss a possible origin of the circumnuclear molecular gas. A distance of 12.8 Mpc toward NGC 2685 is adopted based on a heliocentric recession velocity of 870 km s^{-1} (Shane 1980) and a galactocentric correction of 88 km s^{-1} with a Hubble constant of 75 km s^{-1} Mpc^{-1}. Therefore, our beam size (15 arcsec) corresponds to 820 pc in a linear dimension. Basic data of NGC 2685 compiled from the literature are given in Table I.

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TABLE I. Basic data of NGC 2685.

Quantity	Symbol	Units		Reference
Right assencion	$\alpha(1950)$		$8^h\ 51^m\ 41.2^s$	Dressel and Condon (1976)
Declination	$\delta(1950)$		+58° 55' 30"	Dressel and Condon (1976)
Morphology			S0 pec	RC2[b]
Heliocentric velocity	$v_\odot$(HI)	km s^{-1}	870	Shane (1980)
Blue magnitude	B_T^0	mag	11.51	RC2[b]
Color	$(B-V)_T^0$	mag	0.76	RC2[b]
Distance	D	Mpc	12.8	This paper
HI mass	$M_{\rm HI}$	$M_\odot$	1×10^9	Shane (1980)[a]
FIR flux	$S_{12\mu m}$	Jy	< 0.25	Fullmer and Lonsdale (1989)
	$S_{25\mu m}$	Jy	< 0.25	Fullmer and Lonsdale (1989)
	$S_{60\mu m}$	Jy	< 0.40	Fullmer and Lonsdale (1989)
	$S_{60\mu m}$	Jy	0.35	Thronson *et al.* (1989)
	$S_{100\mu m}$	Jy	1.89	Fullmer and Lonsdale (1989)
	$S_{100\mu m}$	Jy	1.8	Thronson *et al.* (1989)
FIR luminosity	$L_{\rm FIR}$	$L_\odot$	2.2×10^8	Thronson *et al.* (1989)[a]
Radio continuum flux	$S_{\rm 1415MHz}$	mJy	< 3	Hummel and Kotanyi (1982)
X-ray luminosity	L_X(0.5-4.5 kev)	$L_\odot$	5.5×10^5	Forman, Joens, and Tucker (1985)

[a] The HI mass and the FIR and X-ray luminosities are rescaled to our adopted distance.
[b] RC2 = Second Reference Catalog of Bright Galaxies (de Vaucouleurs, de Vaucouleurs, and Corwin 1976).

II. OBSERVATION AND RESULTS

a) Observations

The observation of the ^{12}CO ($J=1$-0) emission was made with the 45 m telescope of the Nobeyama Radio Observatory in January 1990 in an observational program of *CO Survey of Arp's Peculiar Galaxies* (Sofue *et al.* 1990). The measured HPBW and the main-beam efficiency at 115 GHz were 15 arcsec and 0.36, respectively. The pointing was checked by using an SiO maser source R-Lyn. The observing condition was very good (clear sky and zero wind velocity). The pointing accuracy was better than about ± 2 arcsec (peak value).

The receiver front end was a cooled Shottky barrier diode mixer receiver. The system noise temperature $T_{\rm sys}$ (SSB) including the atmosphere effect and the antenna ohmic loss was 700 K. The backend was the 2048-channel wide-band 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 signal-to-noise ratios, the final data were smoothed by 64 channels, and thus the final velocity resolution was 20 km s^{-1}. We used the position-switching mode of observation, and the total integration time on source was 25 min in total.

b) Results

Figure 1 [Plate 94] shows the CO spectrum of NGC 2685. The emission feature is observed in a velocity range between 830 and 1000 km s^{-1}. The emission profile shows a flat-top feature with a peak antenna temperature of $T_A^* \simeq 50$ mK. The central CO velocity, 915 km s^{-1}, is in agreement with the H I velocity of 870 km s^{-1} (Shane 1980).

The integrated CO intensity is estimated by

$$I_{\rm CO} = \int T_A^* dv/\eta_B \quad ({\rm K\ km\ s^{-1}}), \tag{1}$$

where η_B is the main beam efficiency of the telescope; $\eta_B = 0.36$. The observed integrated CO intensity is 17.6 ± 1.4 K km s^{-1}. The quoted error is an rms noise.

The mass of molecular gas $\mathscr{M}_{\rm H_2}$ is estimated by a relation (Scoville *et al.* 1987),

$$\mathscr{M}_{\rm H_2} = 5.8\times10^6\ I_{\rm CO} A (\mathscr{M}_\odot), \tag{2}$$

where A is the projected area of a 15″ FWHM beam (in kpc^2). As a result, we obtain $7.0\times10^7\ \mathscr{M}_\odot$. It should be noted that this value is smaller by an order of magnitude than the previous upper limits by Rowan-Robinson, Phillips, and White (1980), Johnson and Gottesman (1980), and Thronson *et al.* (1989). Our results are summarized in Table II together with the previous CO observations.

The estimate of molecular gas mass is influenced by several cloud parameters such as temperature, density, and chemical abundance (Maloney and Black 1988). However, we adopt the above relation because it has been usually used on other galaxies in the literature, making a consistent comparison possible.

III. DISCUSSION

a) Kinematical Properties of the Molecular Gas Clouds

The observed CO emission profile (Fig. 1) shows a flat-top feature rather than a Gaussian-like profile although the S/N ratio is not enough to discuss the line profile in more detail. It is likely that the molecular gas is distributed either like a disk or a ring and is rotating around the nucleus of NGC 2685. Hereafter, we call this the circumnuclear molecular gas. The observed linewidth (FWHM) of CO emission is about 170 km s^{-1}. This value is nearly consistent

TABLE II. Results of the CO observations.

Telescope	HPBW (arcsec)	$I_{\rm CO}$ (K km s^{-1})	FWHM (km s^{-1})	$M_{\rm H_2}$ ^{a} ($M_\odot$)	References
NRO 45 m	17	14.7±1.2	170	7.5×10^7	1
NRAO 11 m	66	$T_{\rm A}^*(3\sigma) < 0.18$ K	—	$< 5.2 \times 10^8$	2
NRAO 11 m	66	$T_{\rm A}^*(3\sigma) < 0.20$ K	—	—	3
FCRAO 14 m	45	0.7^b	—	$< 1.6 \times 10^8$	4

References: 1) This paper, 2) Johnson and Gottesman (1980), 3) Rowan-Robinson, Phillips, and White (1980), and 4) Thronson *et al.* (1989).

[a] A distance of 12.8 Mpc is adpoted.

[b] A velocity width of 300 km s^{-1} is assumed.

with H I and optical (emission and absorption) ones along the minor axis (Shane 1980; Ulrich 1975; Schechter and Gunn 1978). However, it is difficult to clarify whether the circumnuclear molecular gas is associated with the helix or with the S0 main body. Here we assume that the helix and the S0 galaxy have their kinematical center at the same position. Since no H I gas is associated with the main body (Shane 1980), it is more likely that the circumnuclear molecular gas is associated with the helix; namely it comes from the gas contained in the helix, while it exists near the nucleus of the S0 galaxy.

b) Circumnuclear Molecular Gas and the Nuclear Activity in NGC 2685

The present observation shows that NGC 2685 has molecular gases of $7.0\times10^7\ \mathscr{M}_\odot$ in its 15 arcsec (= 820 pc) central region. If we assume that these gas clouds are distributed uniformly in the beam, we obtain a mean surface mass density of molecular gases as $5.4\times10^7\ \mathscr{M}_\odot\ {\rm kpc}^{-2}$, which is corrected for the galactic inclination ($i = 58°$; Balkowski 1979). This value is comparable to an average value of $5.5\times10^7\ \mathscr{M}_\odot\ {\rm kpc}^{-2}$ for starburst nucleus galaxies in which CO emission was detected (Taniguchi, Kameya, and Nakai 1989, 1990). In this section, we discuss how the observed molecular gas is related with the star-forming or nonthermal activity in the nuclear region of NGC 2685.

In the direct photograph (Fig. 1), there can be seen several condensations along the helix structure, which are *off-nuclear* H II regions (Ulrich 1975; Nicholson *et al.* 1987). On the other hand, there is no direct evidence for star formation in the nuclear region. Optical spectroscopic observations by Ulrich (1975) and Schechter and Gunn (1978) showed that [O II] emission is observed with moderate intensity in the central 10 arcsec region of NGC 2685. On the other hand, no Balmer (Hα and Hβ), [N II], and [S II] emission lines are observed in the nuclear region (Heckman, Balick, and Crane 1980; Stauffer 1982) while the [O III] emission is detected in the central 6 arcsec region (Heckman, Balick, and Crane 1980). Although the [O II] emission is frequently (40%–50%) observed in early-type galaxies (ellipticals and S0's: Caldwell 1984; Phillips *et al.* 1986), such ionized gas may be irrelevant of star-forming activity in many cases because the ionized gases show LINER-like excitation (cf. Phillips *et al.* 1986). In the case of NGC 2685, the observed excitation conditions of the nuclear ionized region ([O II]/[O III] = 2.7 and [O III]/Hβ > 1.5: Heckman, Balick, and Crane 1980) are consistent with those of LINERs (cf. Baldwin, Phillips, and Terlevich 1981).

Thronson *et al.* (1989) made a line-add analysis of *IRAS* data of NGC 2685 and estimated a dust temperature of $T_{\rm dust} = 27$ K based on 100–60 μm flux ratio assuming a λ^{-1} dust emissivity law. [Note that only an upper limit of 0.4 Jy is given for the 60 μm flux of NGC 2685 in *Catalogued Galaxies and Quasars Observed in the IRAS Survey,* Version 2 (Fuller and Lonsdale 1989)]. The above temperature is rather low in comparison with those of so-called starburst galaxies; e.g., $T_{\rm dust} \simeq 40$ K (Taniguichi, Kameya, and Nakai 1990). This also indicates that the star-forming activity is low in NGC 2685. Using the far-infrared (FIR) luminosity, Thronson *et al.* (1989) obtained an upper limit of the star-formation rate of $0.14\ \mathscr{M}_\odot\ {\rm yr}^{-1}$, which is quite lower by one or two orders of magnitude than those of starburst galaxies studied by Bushouse (1987).

Further, we discuss the ratio of $L_{\rm FIR}/\mathscr{M}_{\rm H_2}$ which is an indicator of star-formation efficiency (cf. Young *et al.* 1986a,b). NGC 2685 has a ratio of $L_{\rm FIR}/\mathscr{M}_{\rm H_2} = 3$. This value is similar to that of the Andromeda galaxy M31 ($L_{\rm FIR}/\mathscr{M}_{\rm H_2} = 2$; Young *et al.* 1986a). S0 galaxies studied by Thronson *et al.* (1989) tend to have low ratios; $L_{\rm FIR}/\mathscr{M}_{\rm H_2} = 6 \pm 1$ for six S0 galaxies. On the other hand, Young *et al.* (1986b) obtained that the values of $L_{\rm FIR}/\mathscr{M}_{\rm H_2}$ are 12 ± 3 and 78 ± 16 for isolated spiral galaxies (from Sb to Scd) and interacting/merging galaxies, respectively. Therefore, it is concluded that the star-formation efficiency in the nuclear region NGC 2685 is significantly low, although the surface density of molecular gas is not different from those of starburst-nucleus galaxies.

c) Origin of the Circumnuclear Molecular Gas

Early-type galaxies (E's and S0's) have been observed as gas-poor stellar systems. Faber and Gallagher (1976) first claimed that an expected return gas mass from evolved and/or died stars during a Hubble time exceeds an upper limit mass of neutral hydrogen. This dilemma was partly solved by Forman, Jones, and Tucker (1985) by detecting hot coronal gas with a mass of $10^{9-10}\ \mathscr{M}_\odot$ in such early-type galaxies by their x-ray observations. They interpreted that such hot gas may be accumulated from mass loss during stellar evolution and may be heated by supernova explosions. Arimoto and Yoshii (1987) successfully explained photometric and chemical properties of elliptical galaxies in terms of a supernova wind-driven model.

Although, in some early-type galaxies, much H I gas has been detected, Knapp, Turner, and Cunniffe (1985) and Wardle and Knapp (1986) studied statistical properties of H I gas in ellipticals and S0's and showed that frequency distributions of $\mathscr{M}_{\rm H\,I}/L_B$ ratios of E's and S0's are significantly different from that of late-type spiral galaxies. Thus, they concluded that H I gases in early-type galaxies are external in origin; i.e., accretion from a gas-rich partner or an intergalactic H I cloud. Further, concerning polar-ring galaxies, the presence of ring inclined to the main galaxy favors the external origin of gases from a colliding/merging partner (cf. Schweizer, Whitmore, and Rubin 1983).

In the case of NGC 2685, according to the mass return rate from evolved stars [$\dot{\mathscr{M}}_{\rm rtn}(\mathscr{M}_\odot {\rm y}^{-1}) = 10^{-10}\ L_B\ (L_\odot)$ Faber and Gallagher 1976; see also Thronson *et al.* 1989], the accumulated mass during a Hubble time ($\simeq 10^{10}$ yr) amounts to more than $10^9\ \mathscr{M}_\odot$ (the *B* luminosity of NGC 2685 is about $6\times10^9\ L_\odot$) which is nearly comparable with the H I mass (Shane 1980). Note that the hot gas mass estimated by the x-ray observation (Forman, Jones, and Tucker 1985) may be less than $2\times10^8\ \mathscr{M}_\odot$ (Thronson *et al.* 1989) and the mass of molecular gas detected by us only amounts to $7.0\times10^7\ \mathscr{M}_\odot$. It is possible that the observed gas is supplied from the returned gas. However, most of the returned gas may have gone out of the galaxy through the process of supernova explosions like in elliptical galaxies (Arimoto and Yoshii 1987).

It is difficult to conclude whether the gas in NGC 2685 is internal in origin or not, because the above discussions are not unambiguous. However, as discussed in Sec. III*a*, the circumnuclear molecular gas clouds may be associated with H I gas. Further, the structure of the outer ring is significantly disturbed (see Fig. 1). Therefore, it is more likely that the most of molecular gas is external in origin.

d) Comments on NGC 2685 as a Polar-Ring Galaxy

Here we have a fundamental question that NGC 2685 is a typical polar-ring galaxy because this galaxy has an outer ring rotating around the kinetimatical axis of the main body (see the overexposed photograph of Fig. 1). Shane (1980) proposed an idea of different origin of the two rings: The outer ring is of old age, usually seen in early-type barred spiral galaxies, while the polar ring may be formed by a recent accretion event. However, we note that the outer ring also shows a morphological peculiarity (see the overexposed photograph in Fig. 1), suggesting a possibility that the origin of the outer ring is also external. Since the helix structure is warped, it may be linked with the faint outer ring.

There are two ways to settle the problem on the presence of polar ring: one is that the accretion plane is eventually orthogonal to the disk plane of the host galaxy, and the other is that the polar ring is now settled in one of the preferred planes of the host galaxy (see Schweizer, Whitmore, and Rubin 1983). Neither cases are applicable to NGC 2685 because this galaxy has two rings, as noted before. It should be also reminded that the main body of NGC 2685 is not a *spindle* (i.e., a cigarlike configuration) but a usual oblate disk (Schechter and Gunn 1978). Therefore, the polar configuration does not correspond to a preferred plane of NGC 2685.

It is known that there presents anomalous orbits in a rotating triaxial potential (van Albada, Kotanyi, and Schwarzschild 1982; Heisler, Merritt, and Schwarzschild 1982). One of the anomalous orbits is a retrograde closed orbit caused by the Coriolis force. This kind of orbit provides a possible explanation of the warped dust lane of Centaurus A(= NGC 5128) (van Albada, Kotanyi, and Schwarzschild 1982). In this case, gas clouds can rotate along the minor axis of the main body which is just the case of NGC 2685. It should be remarked here that the ionized gas and H I gas are dynamically decoupled from the S0 main body of NGC 2685. Namely, these gaseous components show a counter rotation with respect to the stellar one (Schechter and Gunn 1978; Ulrich 1975). Hence, the most plausible explanation of the helix of NGC 2685 is as follows: The helix is the retrograde warped ring responding to the rotating triaxial main body and the outer ring roughly parallel to the main body may prefer the principal equatorial plane of the S0 disk.

According to this idea, we expect that a colliding partner lies near the direction of the major axis of the main body of NGC 2685. Inspecting the Palomar Observatory Sky Survey print, we find possible candidates of the partner. They are UGC 4663 (28′ NE) and MCG + 10-13-046 (36′ NE). Although there is no velocity data of MCG + 10-13-046 at present, this galaxy seems to be a distant spiral galaxy. On the other hand, UGC 4683 is a magellanic-type irregular galaxy (see Fig. 2) [Plate 95] and its H I recession velocity (909 km s^{-1}: Fisher and Tully 1981; 927 km s^{-1}: Tifft and Cocke 1988), is quite similar to that of NGC 2685 (870 km s^{-1}; Shane 1980). This galaxy shows a disturbed feature and has faint companions in the direction toward NGC 2685. These observational properties may provide evidence for the interaction with NGC 2685. A projected distance between NGC 2685 and UGC 4683 is about 100 kpc, which seems to be too distant in a usual sense for a galaxy collision. If we assumed a tangential velocity difference of 100 km s^{-1} between NGC 2685 and UGC 4683, a time of 1×10^9 yr would elapse.

The settling timescale of the outer ring structure may be an order of 10^9 yr (Shane 1980). In fact, the ages of polar rings of NGC 4650A and ESO 415-G26 are estimated as $\sim 1\text{–}3\times10^9$ yr and that of A0136-0801 is older than a few 10^9 yr (Whitmore, McElroy, and Schweizer 1987). In addition, Mould *et al.* (1982) estimated an age of less than 3×10^9 yr for the polar ring of UC 7576 based on the color of the ring. Therefore, the presence of the distant companion strengthens our interpretation. The observed H I mass of UGC 4683 is about $1\times10^8\ \mathscr{M}_\odot$ (Tifft and Cocke 1988) while an indicative total mass is estimated as $2\times10^9\ \mathscr{M}_\odot$ (Fisher and Tully 1981). Since the observed H I mass in NGC 2685 is $1\times10^9\ \mathscr{M}_\odot$ (Shane 1980), most of the mass of UGC 4683 may be stripped through the collision and accrete onto NGC 2685. To confirm our picture, theoretical and numerical studies would be desirable.

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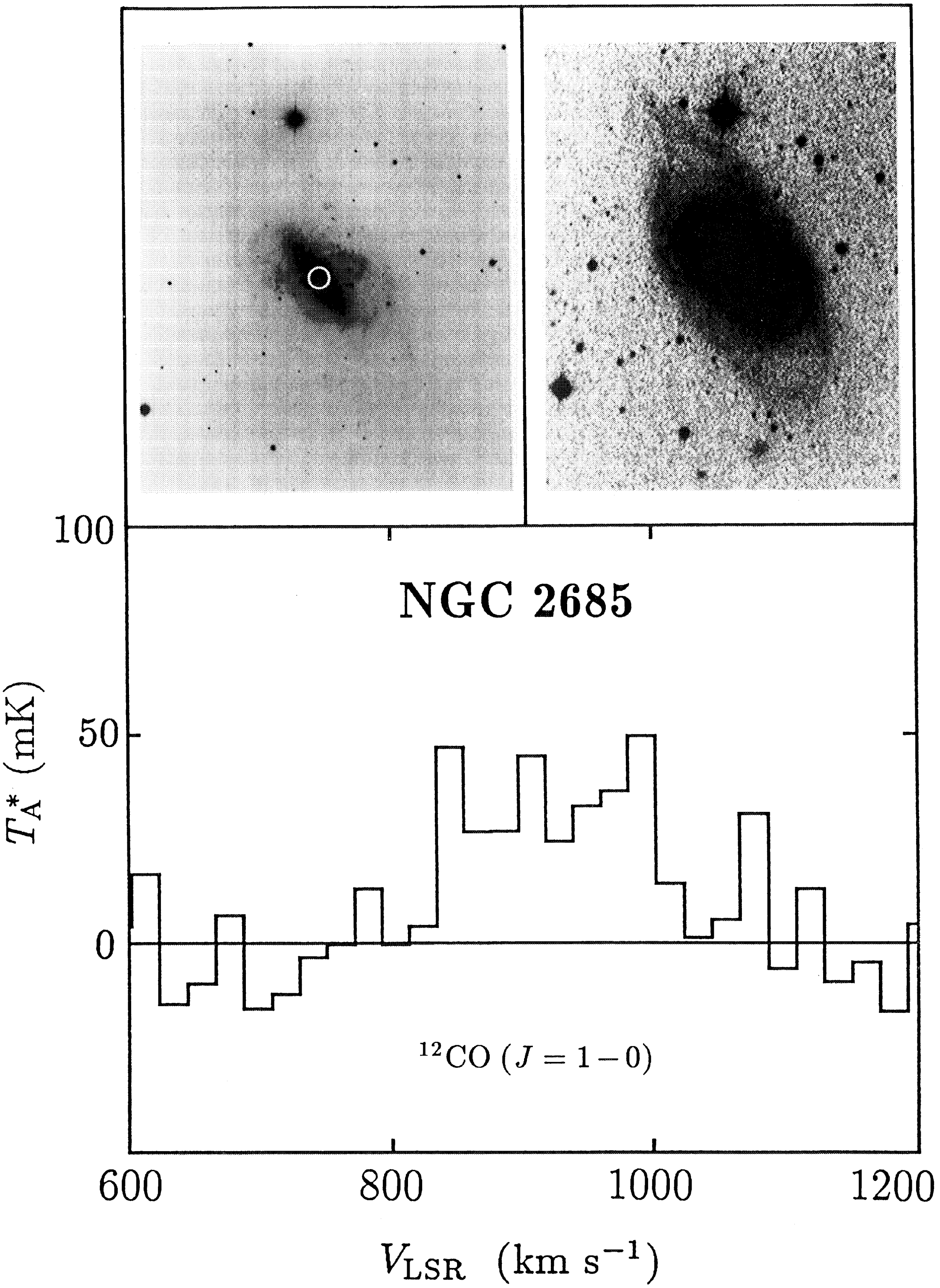

FIG. 1. The ^{12}CO ($J = 1$–0) spectrum of NGC 2685. The ordinate is T_A^*, uncorrected for the beam efficiency. The upper panel shows two direct photographs of NGC 26875: one is taken from Arp's (1966) *Atlas of Peculiar Galaxies* (left panel) and the other from Kormendy (1977) (right panel). The beam size (15 arcsec) is shown by an open circle in the left panel.

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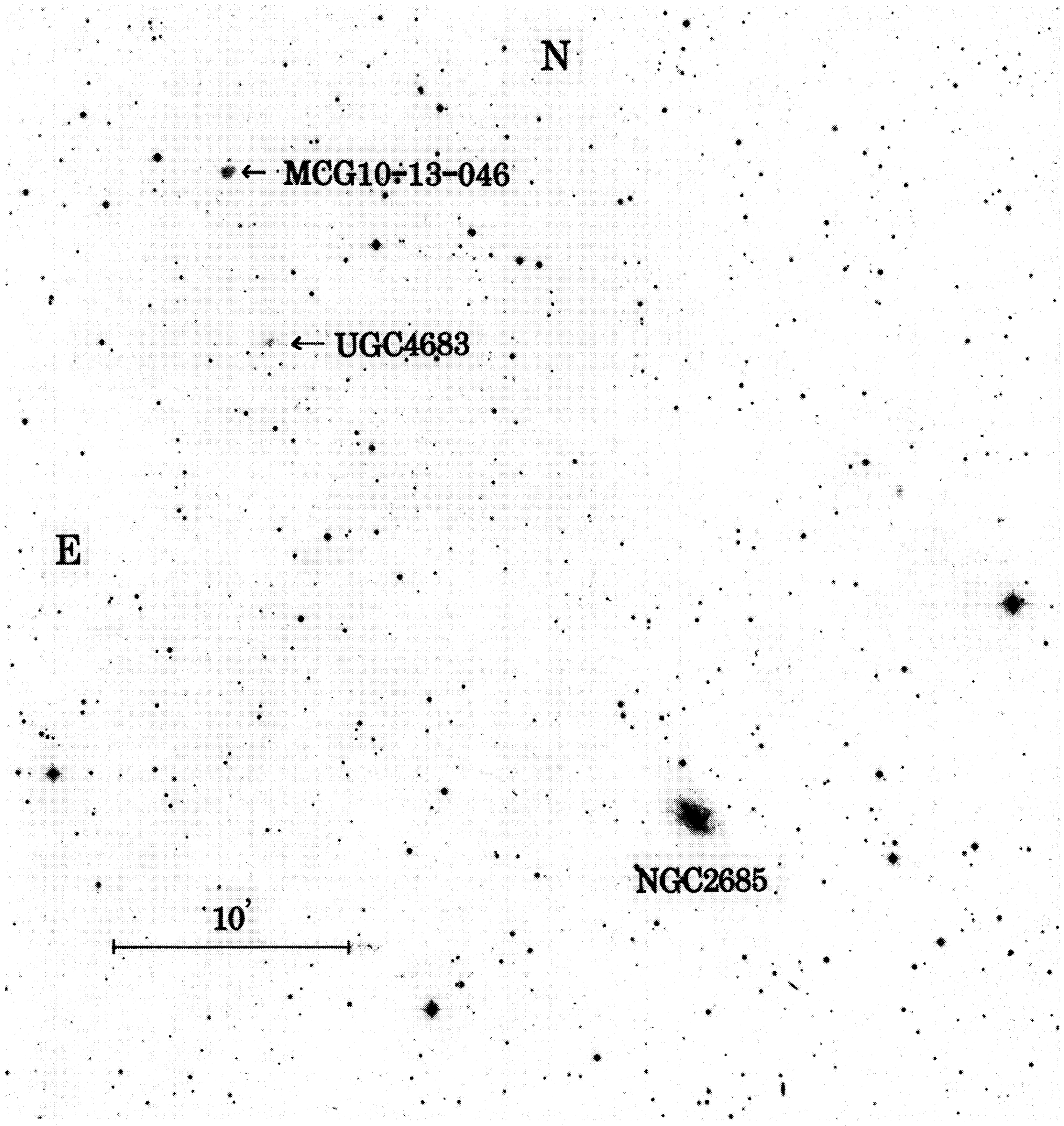

FIG. 2. A photograph of NGC 2685 and a possible distant partner UGC 4683, reproduced from a Palomar Observatory Sky Survey blue print.

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