FIRST INTERFEROMETRIC OBSERVATIONS OF MOLECULAR GAS IN A POLAR RING: THE HELIX GALAXY NGC 2685

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ABSTRACT

We have detected four giant molecular cloud associations (sizes $\lesssim 6.6 \approx 430$ pc) in the western and eastern regions of the polar ring in NGC 2685 (the Helix galaxy) using the Owens Valley Radio Observatory millimeter interferometer. Emission from molecular gas is found close to the brightest H$\alpha$ and H$\beta$ peaks in the polar ring and is confirmed by new IRAM 30 m single-dish observations. The CO and H$\alpha$ line velocities are very similar, providing additional kinematic confirmation that the CO emission emerges from the polar ring. For the first time, the total molecular mass within a polar ring is determined [$M_{H_2} \approx (8-11) \times 10^6 M_\odot$, using the standard Galactic conversion factor]. We detect about $M_{H_2} \approx 4.4 \times 10^6 M_\odot$ in the nuclear region with the single dish. Our upper limit derived from the interferometric data is lower ($M_{H_2} \leq 0.7 \times 10^6 M_\odot$), suggesting that the molecular gas is distributed in an extended ($\gtrsim 1.3$ kpc) diffuse disk. These new values are an order of magnitude lower than in previous reports. The total amount of molecular gas and the atomic gas content of the polar ring are consistent with formation due to accretion of a small gas-rich object, such as a dwarf irregular. The properties of the NGC 2685 system suggest that the polar ring and the host galaxy have been in a stable configuration for a considerable time (a few gigayears). The second (outer) H$\alpha$ ring within the disk of NGC 2685 is very likely at the outer Lindblad resonance of the $\sim 11$ kpc long stellar bar.

Subject headings: galaxies: individual (NGC 2685) — galaxies: ISM — galaxies: kinematics and dynamics

1. INTRODUCTION

Polar ring galaxies (PRGs) represent an unusual, rare class of objects that show clear signs of galaxy interaction (Schweizer, Whitmore, & Rubin 1983). Typically, an early-type (S0 or E) host galaxy is surrounded by a luminous ring (containing stars, gas, and dust) of $\sim 5-25$ kpc diameter oriented almost perpendicular to the main stellar disk and rotating about the center of the main stellar body (see the PRG atlas by Whitmore et al. 1990). To date, only about a dozen PRGs have been kinematically confirmed (e.g., Table 1 in Sparke & Cox 2000). In the generally accepted picture, the formation of polar rings is the result of a “secondary event,” e.g., capture of a satellite galaxy or accretion of material between (tidally) interacting galaxies involving a preexisting S0 galaxy (e.g., Toomre & Toomre 1972; Reshetnikov & Sofonova 1997). Recently, Bekki (1997, 1998) suggested a pole-on merger between two disk galaxies as an alternative formation mechanism. Observations suggest that polar rings are long-lived structures (Whitmore, McElroy, & Schweizer 1987; Eskridge & Pogge 1997). Possible stabilizing mechanisms are self-gravitation in the ring (Sparke 1986) or a massive triaxial halo (Whitmore et al. 1987; Reshetnikov & Combes 1994).

The Helix galaxy, NGC 2685 [D $\sim 13.5$ Mpc; $1'' \sim 65$ pc; (R)SB0 + Pec] is one of the kinematically confirmed PRGs. Two rings are detected in H$\alpha$ line emission that have orthogonal angular momentum vectors (Shane 1980). Optical and near-IR surface photometry (Peletier & Christodoulou 1993) suggest an age of 2–6 Gyr for the inner “polar” ring and therefore a long-lived structure. The younger H$\beta$ regions in the polar ring of NGC 2685 have solar abundances, making accretion of metal-poor material unlikely (Eskridge & Pogge 1997).

2. OBSERVATIONS

NGC 2685 was observed in its CO (1–0) line with three pointings covering the entire polar ring between 2000 April and June using the six-element Owens Valley Radio Observatory (OVRO) millimeter interferometer in its C and L configurations. The resulting baselines (15–115 m) provide a spatial resolution of $\sim 6.6 \approx 430$ pc with natural weighting. The noise per 10 km s$^{-1}$ channel is $\sim 16$ mJy beam$^{-1}$ in the combined data of six tracks. For the intensity map, only emission above the clipping level of 2.5 $\sigma$ was added together.

The IRAM 30 m telescope was pointed toward six positions in NGC 2685 based on the OVRO data (indicated in Fig. 1). Positions N and W1 were observed on 2002 March 11 (the remaining ones on 2002 May 25) in the CO (1–0) and CO (2–1) lines using the two 3 mm receivers (half-power beamwidth HPBW $\sim 21''$) and one 1 mm receiver (HPBW $\sim 11''$). The observations had a total on-source integration time of about 20 minutes (W2) to 65 minutes (N) with an average of 35 minutes per position. The 1 MHz filter banks provided a velocity resolution of $\sim 2.6$ km s$^{-1}$ per channel for the CO (1–0) line and $\sim 1.6$ km s$^{-1}$ per channel for the CO (2–1) line. The final rms in a smoothed 10 km s$^{-1}$ wide channel was about 4 mK at 115 GHz and 6 mK at 230 GHz.

We also used archival 21 cm H$\alpha$ Very Large Array (VLA) data, which are described in Mahon (1992). The spatial resolution of the combined data (BnC and D configurations) is 34''6 $\times 33''7 (12''7 \times 10''8)$ for natural (uniform) weighting with a channel width of 20.7 km s$^{-1}$ and an rms of 1 $\sigma \approx 0.3$ mJy beam$^{-1}$ (0.5 mJy beam$^{-1}$) for natural (uniform) weighting.

3. DISTRIBUTION AND KINEMATICS OF THE ATOMIC AND MOLECULAR GAS

3.1. Atomic Gas

The atomic gas forms two distinct rings with radii of $\sim 2.4''$ and $\sim 0.57''$ that can be easily kinematically distinguished in the VLA channel maps (Fig. 3.3 of Mahon 1992). We calculated separate data cubes that contain only emission from the inner...
and outer rings by blanking the accreting component in the individual channel maps (Fig. 2). The velocity field of each component is well ordered and shows the spider diagram typical of an inclined rotating disk. We used tilted-ring fitting routines to derive the kinematic parameters (inclination, position angle, dynamical center, systemic velocity) and the H I rotation curve. The position angle (P.A. = 35° ± 1°) of the major axis of the outer H I ring is aligned with the major axis of the S0 host disk (P.A. ~ 37°; Fig. 3). The position angle of the inner polar ring is offset by about 70°. However, the inclination derived for the two H I gas rings and the inner S0 host are similar (i ~ 65°) within the errors (see also Shane 1980; Mahon 1992). For the final rotation curve, we assumed that the rotation velocities in the polar ring reflect those in the H I disk at the corresponding radii (Fig. 3). The rotation curve is consistent with solid-body rotation out to a radius of ~50′′ (3.3 kpc), which includes the position of the polar ring (r ~ 0′′.57 = 2.2 kpc).

**Outer H I ring.**—The outer H I ring is situated at a radius of r ~ 2′.4 (~9.4 kpc) in a large-scale (r ~ 2′.6 = 10.1 kpc) diffuse disk. The H I column density exceeds ~1 × 10^{21} cm^{-2} in a few locations within the outer ring at scales of ~10′. The outer ring contains an atomic gas mass of about 8.8 × 10^{8} M_\odot, or about 62% of the total atomic gas mass (1.41 × 10^{9} M_\odot). In the DSS2 red image, a very faint ringlike structure surrounding the main stellar disk (see also Peletier & Christodoulou 1993) coincides with the H I ring (Fig. 3). The change in position angle and ellipticity at r ~ 80′′~90′′ is indicative of a bar with a similar semimajor axis length (Fig. 3). If we assume the standard relation between the corotation resonance (CR) radius and the bar semimajor axis α (r_{CR} = 1.2α), we find r_{CR} ~ 100′′ and a bar pattern speed of Ω ~ 25~30 km s^{-1} kpc^{-1}. The position of the outer Lindblad resonance (OLR) lies approximately at the radius of the H I ring under these assumptions (Fig. 3).

**Polar H I ring.**—The Hα image by Eskridge & Pogge (1997) shows about 20 H II regions that delineate the polar ring (Fig. 1). The H I polar ring coincides with the Hα and optical continuum emission forming the polar ring (Figs. 1 and 2). The polar H I ring contains about 2.9 × 10^{8} M_\odot, or ~20%, of the total atomic gas mass. This is about 4% of the dynamical mass at this radius [M_{dyn}(r = 34′′) = 7.4 × 10^{8} M_\odot, assuming spherical symmetry]. The average H I column density in the western part of the polar ring is about 1.4 × 10^{21} cm^{-2} (peak of 2.1 × 10^{21} cm^{-2}). In the eastern part, the average H I column density is just below 10^{21} cm^{-2} on scales of ~10′.

### 3.2. Molecular Gas

CO (1−0) line emission is detected with the OVRO millimeter interferometer in the eastern and western edges of the polar ring of NGC 2685 (Fig. 1). The CO data are summarized in Table 1. No molecular line emission above 3 μm is seen from the nuclear region, even when smoothed to a spectral resolution of 130 km s^{-1} (1 σ ~ 6 mJy beam^{-1}). The four giant molecular cloud associations (GMAs) in the polar ring are spatially unresolved at our resolution of ~6′′ (~0.30 pc). The molecular gas is located close to the densest H I peaks in the polar ring (Fig. 1), which are also next to the brightest Hα regions. The velocities and line widths of the molecular gas agree well with those seen in the atomic gas of the polar ring (Fig. 4), providing kinematic confirmation that the CO emission is located in the polar ring and not in the S0 host.

![Fig. 1](image1.png)

**Fig. 1.**—Molecular gas as seen in its CO line emission by OVRO *(thick black contours)* is located close to the densest H I peaks *(thin gray contours)* and the H II regions seen in the Hα line emission *(gray scale)*. IRAM 30 m pointings are indicated by dashed circles delineating the 3 mm HPBW. Ellipse indicates the geometry of the polar ring. The beams of the OVRO and H I data are shown.

![Fig. 2](image2.png)

**Fig. 2.**—Intensity maps *(gray scale)* and velocity fields *(contours)* of the VLA H I data. Increasing *(solid lines)* and decreasing *(dashed lines)* velocities are shown in steps of 20 km s^{-1} relative to v_{max} = 875 km s^{-1} *(thick line)*. *(a)* Total H I emission; inset shows an optical image *(from NOAO/AURA/NSF)* of NGC 2685. *(b)* Polar ring component only. *(c)* Outer H I disk/ring.

![Fig. 3](image3.png)

**Fig. 3.** *(a)* Smoothed DSS2 red image *(contours)* overlaid on the H I outer disk/ring component *(see text)*. *(b)* The change in ellipticity e = 1 − b/a and position angle of fitted ellipses to the DSS2 red image *(filled circles)* indicate a bar semimajor axis of ~80′′ *(shaded column)*. The values of Peletier & Christodoulou (1993) derived from a K-band image *(asterisks)* and a deep F-band image *(open circles)* are shown as well. *(c)* The rotation curve derived from the H I data *(solid line)* and the fits to the natural weighted outer disk only *(filled circles)* and to the polar ring *(open circles)*. Corresponding curves for Ω *(dark dashed line)* and Ω + δΩ *(light dashed line)* indicate that the OLR is at about 150′′ *(hatched area)* for a bar semimajor axis length of about 80′.
A comparison of the CO line flux detected in the OVRO data with the IRAM 30 m single-dish line flux in the western (eastern) part of the ring shows that the OVRO data recovers about 90% (40%) of the single-dish flux (Table 1). Both $^{12}$CO lines are detected on both sides of the polar ring with the IRAM single-dish telescope (Fig. 4). The line FWHMs are fairly small ($\sim 8^{\prime\prime}$ to $\sim 22^{\prime\prime}$) for the GMAs (size comparable to those seen in other galaxies (e.g., in M51; Aalto et al. 1999). The properties of the GMAs (size $\leq 430$ pc, velocity widths $\sim 15$ km s$^{-1}$) are comparable to those seen in other galaxies (e.g., in M51; Aalto et al. 1999). Using the upper mass limit of $0.2 \times 10^9 M_\odot$ from position W2 (Table 1), we derive an upper limit for the total undetected molecular gas mass in the polar ring of about $6 \times 10^5 M_\odot$. The central CO (1–0) IRAM spectrum clearly shows a 130 km s$^{-1}$ wide line at the $\sim 3$ $\sigma$ level of $\sim$6 mK. Using the relation $S_\nu/S_\nu = [1 + (\beta_\nu/\beta_\nu)^2]/[1 + (\beta_\nu/\beta_\nu)^2]$ between the ratios of the fluxes ($S_\nu$) and the beam ($\beta_\nu$) and source sizes ($\beta_\nu$; e.g., Dickel 1976) for the IRAM (J) and OVRO (O) data, we find that the extent of the CO emission must be on the order of $\sim 20^{\prime\prime}$ to explain the OVRO nondetection.

### 3.3. Comparison to Previous CO Detections

Our CO line fluxes for the polar ring (regions E1 and W1) are considerably smaller than those previously reported by Watson, Guptill, & Buchholz (1994; their positions 3 and 7). Given the good agreement between our CO line widths ($\sim 20$ km s$^{-1}$) and the H I line width (compared to the CO line widths of $\sim 130$ km s$^{-1}$ by Watson et al. 1994), together with the consistency of the OVRO and IRAM data, we conclude that the present data yield more accurate fluxes. The strong CO (1–0) line emission apparent in the Nobeyama Radio Observatory 45 m spectrum (Taniguchi et al. 1990) is also inconsistent with our nuclear line flux.
gigayears ago during an accretion event (of a dwarf/low-mass
galaxy) similar to those proposed for S0 counterrotators. The
solar metallicity derived for the ring H\textsc{ii} regions (Eskridge &
Pogge 1997) implies that (1) the accreted dwarf galaxy had an
elevated intrinsic metallicity similar to those observed in a couple
local dwarf galaxies (e.g., Mateo 1998), (2) low-level continuous
star formation has enriched the polar ring interstellar medium
(ISM) in the past few gigayears (see, e.g., Legrand et al. 2001),
and/or (3) the ISM of the accreted dwarf galaxy was mixed/
enriched with more metal-rich material from the primary galaxy.
The outer H\textsc{i} ring can be explained as gas accumulated at
the OLR of the 11 kpc diameter bar. The good spatial corre-
spondence of the optical and H\textsc{i} rings suggests that there is
enhanced star formation. We conclude that the suggested sce-
nario by Peletier & Christodoulou (1993) seems unlikely, where
the outer H\textsc{i} ring was formed during the secondary accretion
event that formed the inner polar ring as well.

4.2. Stability of the Polar Ring

The OVRO map of the molecular gas provides the first un-
ambiguous (kinematically confirmed) detection of molecular
gas in a polar ring. This molecular gas is associated with about
four GMAs that are located close to ongoing star formation
and peaks in the atomic gas that exceed \(10^{21}\) cm\(^{-2}\). Note that
the molecular and atomic gas appear concentrated where the
polar ring intersects the disk of the parent galaxy.
The polar ring exhibits at least two stellar populations. The
H\textsc{ii} regions present in the polar ring have an average age of
5 Myr (if instantaneous star formation is assumed) and about
solar metallicity (Eskridge & Pogge 1997). However, Peletier
& Christodoulou (1993) deduced an age of a few gigayears
from the red colors of the polar ring. The contribution of the
atomic gas in the polar ring to the total dynamical mass (en-
closed out to its radius) is about 4%. This might already be
enough to allow for self-gravitation of the polar ring and
explain its persistence (Sparke 1986). Alternatively, Mahon
(1992) has found that the H\textsc{i} distribution and kinematics of
NGC 2685 can be stable using models of prograde anomalous
orbits in a triaxial gravitational potential. Thus, we conclude
that (1) the polar ring has been stable for a substantial time (a
few gigayears), and (2) the recent star formation in the polar
ring has been triggered by another mechanism than the actual
polar ring formation process.

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