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FAST ROTATION IN THE NUCLEAR REGION OF THE GALAXY NGC 1808

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ABSTRACT

We have mapped the $\lambda = 21$ cm absorption in the nuclear region of the starburst galaxy NGC 1808 using the VLA AnB-hybrid array with a resolution of $\approx 5''.2$ ($\simeq 275$ pc). We find that the broad ($\Delta v \approx 360$ km s^{-1}) absorption line seen at low spatial resolution is in fact a much narrower line which shifts its center velocity over the face of the source. The velocity center of the absorption changes from about $+120$ km s^{-1} relative to the systemic velocity in the northwest to -145 km s^{-1} in the southeast, following the rotation pattern in the outer regions of the galaxy. This is interpreted as a thick ring (torus) of cold, dense gas with a rotation velocity of about 250 km s^{-1} and radius 500 pc. From our data the ring is not expanding or infalling rapidly. We suggest that similar H I rings are also present in numerous other galaxies (e.g., NGC 660, NGC 3079, NGC 4945) for which the width of the unresolved nuclear absorption line matches very closely the disk rotation velocity. The gravitational mass required to explain this fast rotation in the center of NGC 1808 is a few times 10^9 $M_\odot$. Apparently the distribution of mass goes as r^{-1} over at least the range from 500 pc to a few kiloparsecs.

Subject headings: galaxies: active — galaxies: individual (NGC 1808) — galaxies: ISM — galaxies: kinematics and dynamics

1. INTRODUCTION

Absorption by neutral atomic hydrogen in luminous spiral galaxies provides an excellent tool to study the gas kinematics in their nuclear regions. Whereas it is difficult to interpret the observed radial velocities from emission studies, absorption measurements have the advantage that the detected lines must come from the near side of the nucleus. Thus redshifts or blueshifts relative to the systemic velocity of the galaxy, $v_{\rm sys}$, unambiguously show infall or outflow of gas, respectively. Since the absorption lines are intrinsically narrow because of the low temperatures of the optically thick gas, typically 30–150 K (Dickey, Salpeter, & Terzian 1979), it is surprising that numerous galaxies show H I absorption over a broad range of velocities (a few hundred km s^{-1}). Some examples are found in the absorption surveys by Mirabel (1982) and Dickey (1982, 1986).

Interferometric studies of individual bright galaxies, e.g., NGC 4945 (Ables et al. 1987), NGC 660 (Gottesman & Mahon 1989), NGC 3079 (Irwin & Seaquist 1991), and NGC 1808 (Koribalski & Dahlem 1992), reveal H I emission and absorption over about the same velocity range. It is remarkable that these galaxies are all *barred* galaxies with high central activity and infrared luminosities of a few times 10^{10} $L_\odot$, often revealing outflow of gas from the inner regions (see references above).

In order to understand the nuclear kinematics in these galaxies—which are probably very much alike—we have to carry out sensitive *high-resolution* H I observations which enable us at least partially to resolve the central continuum. This has been done for the relatively nearby starburst galaxy NGC 1808, and the first results are presented in this *Letter*.

Sections 1.1 and 1.2 give a short overview of the galaxy NGC 1808 and a description of the kinematic models of the nuclear region. In § 2 we briefly report our observations, and § 3 contains the results obtained from these data. The discussion and conclusions follow in § 4.

1.1. *The Galaxy NGC 1808*

The southern galaxy NGC 1808 is a nearby example of an extraordinary type of spiral with nuclear activity; some of its properties are summarized in Table 1. It is a starburst galaxy with a high far-infrared (FIR) luminosity, $\approx 2 \times 10^{10}$ $L_\odot$, at a distance of 10.9 Mpc. Well known are the prominent dust filaments which emerge from the central part of its disk (see Véron-Cetty & Véron 1985; Laustsen, Madsen, & West 1987). In the same region we recently found a velocity anomaly indicating outflow of gas into the halo of NGC 1808 (Koribalski et al. 1992). The galaxy has been classified as "Sbc pec" (Sandage & Tammann 1987) and "RSXS1" (SX = SAB, a mixed type between a nonbarred [A] and barred [B] spiral; de Vaucouleurs et al. 1991), whereas the Hα image clearly reveals a barlike structure of length 6 kpc (Koribalski & Dettmar 1992).

The nuclear region of NGC 1808 contains a number of bright hot spots, which are mostly interpreted as very large H II regions (Sérsic & Pastoriza 1965; Alloin & Kunth 1979; Koribalski & Dettmar 1992). The radial velocities of these hot spots decrease from about 1080 km s^{-1} northwest to 830 km s^{-1} southeast of the nucleus (Arp & Bertola 1970, components A–F in their Fig. 2). In the actual nucleus, however, Véron-Cetty & Véron (1985) draw attention to the presence of a broad Seyfert-like component of Hα with FWHM about 550

TABLE 1

THE GALAXY NGC 1808

Parameter	Value	Reference
Central position:		
R.A. (1950)	$05^h05^m58^s.58$	1
Decl. (1950)	$-37°34'36''.5$	
Distance	10.9 Mpc ($H_0 = 75$ km s^{-1} Mpc^{-1})	2
Systemic velocity	1000 ± 5 km s^{-1} (heliocentric)	3
Inclination	57°	4
FIR-luminosity	2×10^{10} $L_\odot$	5

REFERENCES.—(1) Saikia et al. 1990; (2) Sandage & Tammann 1987; (3) Koribalski et al. 1992; (4) Reif et al. 1982; (5) see Danks et al. 1990.

km s^{-1}. Radio observations at $\lambda = 6$ cm reveal a number of compact (< 1″) components in the central region of NGC 1808, probably supernova remnants with a total minimum energy of more than 2×10^{51} ergs each (Saikia et al. 1990).

1.2. *Kinematical Models of the Nuclear Region*

Figure 1 shows a position-velocity diagram along the major axis of NGC 1808 using the H I data set with a resolution of 15″ × 11″ × 5.2 km s^{-1} (see § 2). The nuclear absorption appears as the negative vertical stripe at the center position. It is remarkable that both the H I emission (*solid lines*) and absorption (*dotted lines*) are observed in the same velocity range of about $v_{sys} \pm 180$ km s^{-1}, whereas they come from totally different regions. The broad line width of the nuclear absorption, like that of similar broad lines in the nuclei of other luminous spiral galaxies (see § 1), could come from either random motions of clouds or fast rotation of a nuclear ring.

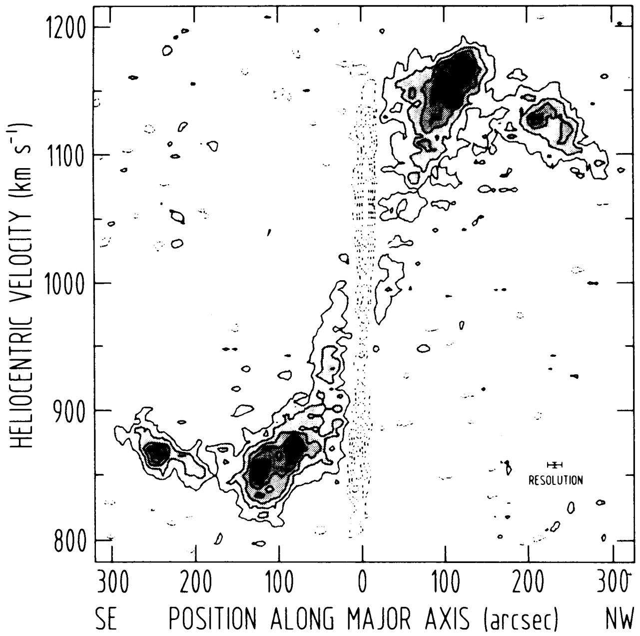

FIG. 1.—Position-velocity diagram along the major axis of the galaxy NGC 1808 (P.A. = 320°, width 15″), using the combined BnC + AnB data set at $\lambda = 21$ cm. Contour levels go from −5.2 to 7.8 mJy $beam^{-1}$, step 1.3 mJy $beam^{-1}$. The resolution is indicated at the lower right.

1.2.1. *Circular Motions*

Ordinary circular rotation of the galactic disk cannot significantly broaden lines, because the nuclear sources are so small that only a narrow column of gas is sampled in absorption. But a *fast-rotating ring very near to the center* is able to explain such a wide range of velocities (see, e.g., Ables et al. 1987; Gottesman & Mahon 1989). The measured radial velocity of gas in such a *nuclear ring* (v_{obs}, relative to v_{sys}) is the projection of the circular velocity, v_{ring}, along the line of sight, i.e., $v_{obs} = (v_{ring}/r_{ring})x$, where r_{ring} is the radius of the ring and x is the impact parameter of the line of sight relative to the center ($-r_{ring} \lesssim x \lesssim +r_{ring}$). To take the inclination of the ring, i_{ring}, into account, v_{ring} has to be corrected by a factor $(\sin i_{ring})^{-1}$.

The signature of such a ring would be a systematic linear velocity shift of the center of the absorption line with position across the face of the continuum source. At any point the line width of the absorption would be much narrower than v_{ring}; roughly it would be given by the velocity gradient v_{ring}/r_{ring} times the beam size in parsecs.

1.2.2. *Noncircular Motions*

Another, more direct explanation for these broad absorption lines is a model with *individual clouds distributed randomly, moving toward and away from the nucleus.* Then broad absorption lines could be the result of several intrinsically narrow features blended together (e.g., Mirabel 1982; Dickey 1986; Van Gorkom et al. 1989). In this case we would expect broad line widths (not depending on the resolution) and no systematic velocity shift with position. A problem with such a model for the compact nuclear regions of spirals like NGC 1808 is that the cloud collision rate should be high. When clouds collide at these supersonic velocities, their kinetic energy should be largely dissipated by heating and radiation of the gas.

2. OBSERVATIONS

In order to determine which of these dynamical models applies for NGC 1808, we have made high-resolution H I observations to map the absorption in front of the nuclear continuum with the VLA[1] BnC- and AnB-hybrid configurations (1990 October and 1991 October, respectively). New observing modes allowed us to use both IFs with 63 channels each, leading to a total number of 104 channels after deleting about 10% of the band edges. The channel separation is 24.424 kHz, corresponding to a velocity resolution of about 5.2 km s^{-1}. The total observing time for each data set was about 15 hr.

Both data sets were reduced with the AIPS software package of the NRAO using mostly standard procedures. The angular resolution obtained after Fourier transformation of the individual and combined data sets varies from 3″.3 × 1″.6 (AnB; "uniform" weighting) to 21″ × 15″ (BnC; "natural" weighting) and is displayed in the corresponding figures. In order to obtain continuum-free channel maps, we subtracted the average of the line-free channels separately for both IFs. The line channels were CLEANed (Högbom 1974; Clark 1980) when allowed by the signal-to-noise ratio. In order to achieve a flat bandpass, we used the cross-correlation normalization mode with the amplitude calibrator 3C 48, which was observed at the beginning and end of each 5 hr observing run.

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[1] The VLA is a facility of the National Radio Astronomy Observatory (NRAO), which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

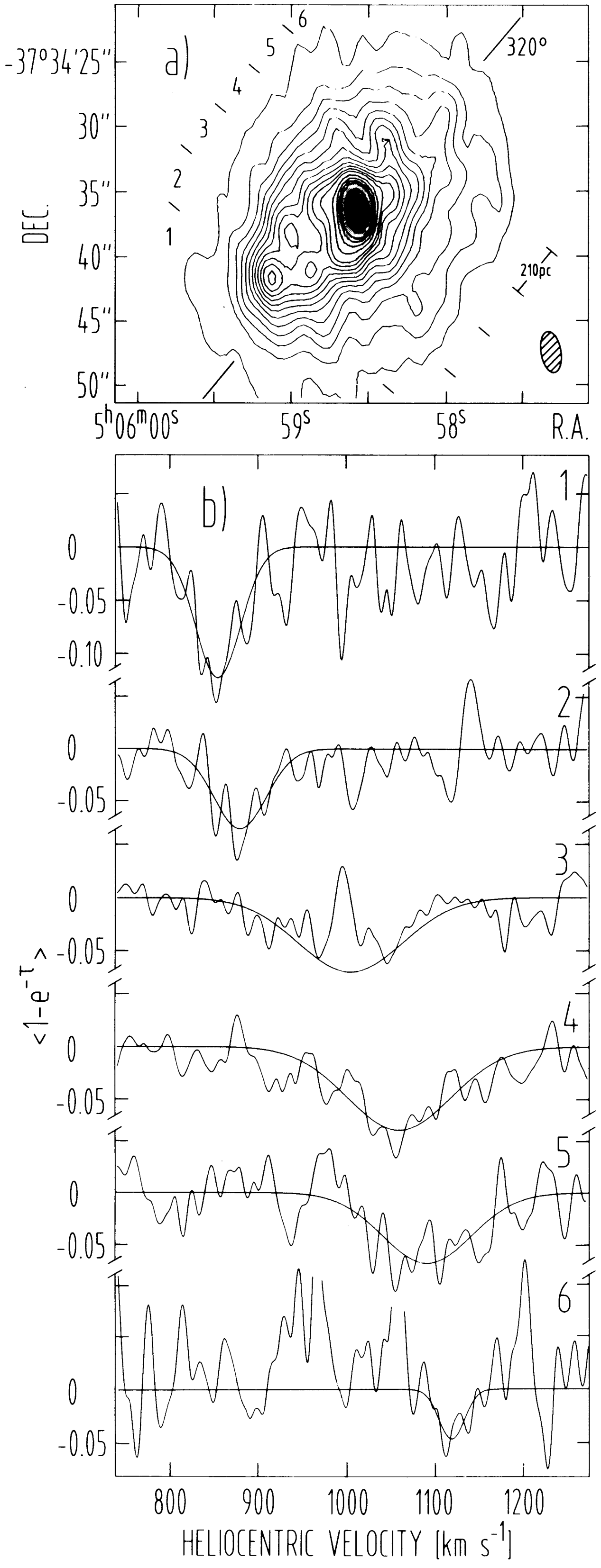

FIG. 2.—(*a*) Contour map of the 21 cm continuum emission of NGC 1808 obtained by averaging the line-free channels of the VLA AnB data set; the resolution is 3"3 × 1"6 using "uniform" weighting. Contour levels are 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 16, 18, 20, 25, 30, and 35 mJy beam^{-1}. Tick marks indicate the division of the continuum into six nearly equally spaced regions along the major axis at P.A. = 320°. (*b*) Optical depth spectra obtained for the regions 1–6 marked in (*a*) and the corresponding Gaussian fits. Here, the "naturally" weighted data cube with a resolution of 5"8 × 4"6 has been used, because of its much better signal-to-noise ratio. Only absorption spectra inside the 10% level of the continuum peak flux have been included. The original channel width of 5.2 km s^{-1} has been smoothed to 16 km s^{-1}.

TABLE 2

PARAMETERS DERIVED FOR AVERAGED ABSORPTION SPECTRA IN FIGURE 2*b*

Region	$v_{\rm center}$ (km s^{-1})	σ_v[a] (km s^{-1})	τ	$\tau_{\rm rms}$
1.........	855 ± 2	60 ± 5	0.13	0.06
2.........	880 ± 2	70 ± 5	0.08	0.04
3.........	1005 ± 3	140 ± 7	0.07	0.03
4.........	1060 ± 2	140 ± 7	0.09	0.03
5.........	1092 ± 4	120 ± 7	0.07	0.04
6.........	1120 ± 5	35 ± 10	0.05	0.07

[a] Not corrected for the channel width.

3. RESULTS

3.1. *Radio Continuum Structure*

The 21 cm continuum map (Fig. 2*a*) with a restoring beam of 3"3 × 1"6 shows extended emission along position angle[2] (P.A.) 320° as well as a number of unresolved ($\lesssim$150 pc) compact radio sources. We can distinguish four components, of which the strongest, with a peak flux of $S_{\rm peak} = 39.2$ mJy beam^{-1}, corresponds to the nucleus defined at $\lambda = 6$ cm by Saikia et al. (1990). The other components have peak fluxes between 10 and 13 mJy beam^{-1}. Here 1 mJy beam^{-1} corresponds to a brightness temperature of 120 K. The integrated flux densities are only slightly higher. The total flux density of the continuum emission in a region of 30" × 20" is about 480 mJy.

3.2. *Absorption-Line Map*

We have mapped the absorption in front of the continuum in order to probe the kinematics of the cool gas in the nuclear region. For presentation we have averaged the absorption spectra (s_i) times the continuum brightness (c_i) toward each pixel (i) in the six strips perpendicular to the major axis of NGC 1808 (see Fig. 2*a*), weighting by continuum brightness squared as described by Dickey, Brinks & Puche (1992, hereafter DBP). Here no attempt was made to interpolate and subtract the line emission against the continuum ($s_{{\rm off},i}$ in DBP), which has been mostly filtered out by the interferometer response. Then, a lower limit for the mean optical depth (τ) spectrum is given by

$$\langle e^{-\tau}\rangle = 1 + \sum_i s_i c_i \sum_j c_j^{-2} . \qquad (1)$$

The optical depth noise ($\tau_{\rm rms}$) for each region is approximately determined by the map rms (here 1.7 mJy beam^{-1}) times the number of pixels in that region and divided by $\sum c_i$ (see DBP). The spectra from the six regions displayed in Figure 2*b* show a clear pattern of rotation, as the center velocities ($v_{\rm center}$) shift with position along the major axis from about −145 to +120

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[2] The position angle of the galaxy has been defined by the angle between north and the receding part of the major axis.

km s^{-1}. The results of Gaussian fitting to the lines as well as the corresponding values for the optical depth τ are given in Table 2. The inferred spin temperatures for the circumnuclear H I gas will be discussed elsewhere.

The observed line widths (σ_v) depend on the number of components sampled by the beam, ranging from 60 km s^{-1} near the edge of the continuum to 140 km s^{-1} in the central region. The latter roughly determines the ratio $v_{\rm ring}/r_{\rm ring}$, which is about 500 km s^{-1} kpc^{-1} within a mean beam size of 5″.2 $\simeq$ 275 pc.

The narrow component that appears in region 3 near the systemic velocity ($v_{\rm center} = 997$ km s^{-1}) is probably caused by emission of gas from the foreground disk.

4. DISCUSSION AND CONCLUSIONS

The absorption spectra against the nuclear continuum of NGC 1808 show a systematic shift of velocity with position, which rules out the possibility of purely turbulent gas in front of the continuum source. A fast-rotating gas component in/around the central region is revealed by the data. Considering the inclination of the NGC 1808 disk, $i = 57°$, the gas is probably concentrated in a thick ring (torus) of radius $\approx$500 pc, which here corresponds to a ring velocity of about $v_{\rm ring} = 250$ km s^{-1}. The ring radius cannot be much smaller than 500 pc, since we see absorption across the entire extent of the continuum, nor can it be much larger, because that would require unreasonably high rotational velocities. From the data we also know that the H I ring is not expanding rapidly (<20 km s^{-1}), since the systemic velocities obtained from the emission and absorption lines are about the same. The radius and velocity of the ring are comparable to the distribution and kinematics of the optically visible "hot spots" (see Arp & Bertola 1970; Koribalski & Dettmar 1992). The possibility of a molecular gas ring has been considered by Dahlem et al. (1990). The gravitational mass, $M_{\rm grav}$, required to explain this fast rotation is a few times 10^9 $M_\odot$. The ratio $M_{\rm grav}/L_{\rm FIR}$ is then $\approx$0.1 inside the inner 500 pc. Taking a spin temperature $T_{\rm spin} = 100$ K, the H I gas mass in such a thick ring would be a few times 10^7 $M_\odot$. Since the velocity range observed in emission is about the same as in absorption, the mass distribution must go as r^{-1} to keep the rotation curve flat beyond a radius of at least 500 pc.

We suggest that the broad velocity range of the H I absorption lines in the central region of other luminous spirals (e.g., NGC 660, NGC 3079, NGC 4945[3]) is also caused by a fast-rotating ring of cold gas. The accretion of gas in the inner region (probably at the inner Lindblad resonance) could have been induced by the bar potential of these galaxies (see, e.g., Combes & Gerin 1985). Since outflow of gas from the central region is another phenomenon observed in this class of galaxies, we propose a scenario in which the neutral gas is fueling the active nucleus where it is partially ionized and then ejected by supernova explosions and winds.

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[3] In NGC 4945 Koornneef (1993) has very recently shown the existence of circumnuclear molecular hydrogen with rotational velocities of 200–250 km s^{-1} at a galactic radius of 100 pc.

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