EVOLUTION IN DUST LANE ELLIPTICALS: DETECTION OF ACCRETED MOLECULAR GAS

LESLIE J. SAGE

Max-Planck-Institut für Radioastronomie, Bonn; and Department of Physics, University of Nevada at Las Vegas, Las Vegas, NV 89154

AND

GIUSEPPE GALLETTA

Dipartimento di Astronomia, Università di Padova, Vicolo Osservatorio 5, 35122 Padova, Italy

Received 1992 July 20; accepted 1993 July 2

ABSTRACT

The detection of moderately large quantities of molecular gas in three minor axis dust lane elliptical galaxies is reported. Masses of H_2 between 4×10^8 and $2 \times 10^9 M_\odot$ have been observed in NGC 1316, NGC 1947, and NGC 5266. The distribution of the molecular gas follows the dust, which is patchy in NGC 1316, around the nucleus in NGC 1947, and in a ring in NGC 5266. The velocities and directions of motion for the CO agree with those of the ionized gas, which rotates perpendicularly to the stars.

Based upon dynamical studies of interacting systems, and following related work on the origin of the H I and ionized gas, we suggest that the H_2 comes from gas acquired from an external source, probably through the ingestion of a gas-rich dwarf galaxy. Since dwarfs, though typically rich in H I, are notably poor in H_2 , some mechanism must exist which converts the atomic into molecular gas. This may be the result of gas compression inside the ring into which the accreted object is smeared.

Following the current theoretical models, the three observed galaxies are situated along a possible evolutionary sequence, with NGC 1316 in the earlier stages of gas (or satellite) accretion and NGC 5266 in a smooth, evolved configuration. The distribution of the molecular gas is entirely consistent with the models.

Subject headings: dust, extinction — galaxies: elliptical and lenticular, cD — galaxies: interstellar matter — galaxies: kinematics and dynamics — ISM: molecules

1. INTRODUCTION

Interactions between galaxies are of great importance in modifying the morphology of stable systems. The smooth structure of elliptical galaxies is suspected to be the result of old, energetic mergers (Barnes 1989), which injected huge quantities of kinetic energy into the system, destroying the structure of the previous galaxies. X-ray emission, coming from gas heated to very high temperatures, is often detected in the intrinsically brighter ones, but ellipticals appear to be particularly poor in cool gas (Roberts et al. 1991). On the other hand, chance ingestions (accretions) of satellite or nearby dwarfs will probably not result in the wholesale restructuring of the accreting system but could, for some period, alter its morphology.

The process of gas accretion is a dynamical phenomenon, and its occurrence is expected in all Hubble types (see Galletta 1991). Very centrally condensed H_2 , with most of the gas mass within the inner ~ 500 pc radius, has become recognized as a feature of strongly interacting and merging galaxies (i.e., Arp 220) where the star formation is very efficient (e.g., Scoville 1991). This probably arises as most of the gas content of the two merging galaxies is converted to H_2 near the center of the resulting system. This scenario can easily explain the observed properties of Arp 220 and other far-infrared (FIR) ultra-luminous galaxies but is very different from the accretion events leading to polar ring galaxies, or ellipticals with minor axis dust lanes.

The peculiar appearance of minor axis dust lane ellipticals (Bertola & Galletta 1978) such as NGC 5128 (Cen A), and of

polar ring S0's (Schweizer, Whitmore, & Rubin 1983) such as NGC 2685 (The Spindle) is generally attributed to some type of accretion. Gas counterrotation in Es and S0's, i.e., gas disks rotating opposite to the stars (Bettoni 1984; Caldwell, Kirshner, & Richstone 1986; Galletta 1987), is another result of accretion. Whitmore et al. (1990) discussed the frequency of such objects and produced a catalog which now includes several tens of members.

Among the few ellipticals where CO emission has been detected (Gordon 1991; Young & Scoville 1991; Roberts et al. 1991) are objects like NGC 5128 and NGC 5363, which belong to the category of minor axis dust lane ellipticals. This seems to support the idea of gas content and distribution fed by a collision.

The comparison of different morphologies of accreted gas (disk or rings in ellipticals; rings only in S0's) and the lack of polar rings in spiral galaxies suggests that the evolution of such structures is fast when some gas preexists in the galaxy (Galletta 1991). The presence or absence of this gas near the galaxian center at the time of interaction should be the parameter that controls the production of a disk of ionized gas and dust, as in NGC 5128 and NGC 1947, or a ring as in NGC 5266 and NGC 4650A. According to this hypothesis, any preexisting gas, upon interacting with accreted material, would, through compression and subsequent cooling, form molecular clouds. This could eventually lead to a period of star formation activity. The quantity of H_2 remaining after the accretion will be a function of the mass of preexisting gas, the mass of the accreted object, and of the star formation rate induced by the collision. In addition, we expect that the distribution of the resulting molecular clouds will not reflect the symmetry of the host systems, but rather that of the collision.

¹ Based on observations collected at the European Southern Observatory, La Silla, Chile.

To test this hypothesis we selected three elliptical galaxies with dust lanes along their minor axes and determined the distribution of the molecular gas through observations of the CO $1 \rightarrow 0$ line at $\lambda = 2.6$ mm. The objects, NGC 1316 (For A), NGC 1947, and NGC 5266, all belong to the same category as NGC 5128 (Cen A), and may represent the same phenomenon at three different evolutionary stages, as we will show in the following discussion.

2. OBSERVATIONS AND DATA ANALYSIS

The data were obtained 1992 March 20–26 and 1993 January 22–26 using the 3 mm cooled Schottky receiver at the Swedish-ESO-Submillimeter Wave Telescope (SEST), where the beam size at 115 GHz is HPBW = $43''$. Typical system temperatures, on the Rayleigh-Jeans main beam temperature scale (T_{mb}), ranged between 650 and 850 K, with some observa-

tions from the first run made in poorer weather ($T_{\text{mb}} \sim 1000$ K). The data were obtained using the double beam-switching mode with a beam throw of $12'$. The backend was the 728 channel $\times$ 0.69 MHz per channel acousto-optical spectrometer. Pointing was checked every 2–3 hr, using the SiO maser sources R Dor, VY CMa, and W Hya, which are near the sample galaxies in the sky. Changes in pointing offsets during the same transit were typically $\lesssim 4''$. On different nights, the offsets for the same region of sky could change by up to $\sim 8''$.

The scans for each source and position were co-added, Hanning-smoothed, and replotted at a channel spacing of ~ 29 km s^{-1} . A linear baseline was then fitted and subtracted from the smoothed spectra. Total integration times per point were typically 4 hr, but ranged from 48 minutes to 10 hr. The final results are shown in Figures 1, 2, and 3 with the corresponding line parameters listed in Table 1. The uncertainties associated

FIG. 1.—The spectra obtained toward NGC 1316, with the offsets indicated. Temperatures are in Rayleigh-Jeans main-beam brightness units, and velocities indicate redshift with respect to the Sun. The positions of the beam on the galaxy are indicated on the sketch of dust lanes from Schweizer (1980).

FIG. 2.—The spectra from NGC 1947, with the additional result from the convolution of all pointings with a 65'' Gaussian beam. A picture of NGC 1947 from the 3.9 m AAT telescope, indicating the size of the SEST beam, is also shown.

TABLE 1
THE OBSERVED GALAXIES

Name	$\alpha(1950.0)$	$\delta(1950.0)$	$\Delta\alpha$	$\Delta\delta$	I_{CO} (K km s ⁻¹)	v_{CO} (km s ⁻¹)
NGC 1316.....	03 ^h 20 ^m 47 ^s .0	−37°23′06″	0″	0″	2.0 ± 1.0	...
			21	−21	2.72 ± 0.24	1520
			−21	21	< 2.7 ^a	..
			−12	48	3.74 ± 0.58	1820
NGC 1947.....	05 26 28.0	−63 48 06	0	0	6.34 ± 0.35	1160
			0	21	5.45 ± 0.47	1200
			21	0	< 3.0 ^a	...
			−21	21	< 3.0 ^a	...
			Convolved		3.88 ± 0.41	1170
NGC 5266.....	13 39 56.0	−47 55 06	0	0	4.59 ± 0.58	2960
			4	14	1.16 ± 0.38	2850
			−4	−14	< 4.4 ^a	...

^a 3 σ .

FIG. 3.—The spectra from NGC 5266, along with a picture (AAT telescope) showing the SEST beam size. The spectrum from the $(-4, -14)$ position has not been presented, since the noise level is much higher than the expected signal. (This was the position with the shortest integration time.) The spectrum therefore conveys no relevant information.

with each integrated intensity are the quadratic sums of errors due to noise in the spectrum

$$\Delta I_n = T_{\text{rms}} \Delta v_i (\Delta v_c / \Delta v_i)^{1/2}$$

and uncertainty in determining the baseline

$$\Delta I_b = T_{\text{rms}} \Delta v_i (\Delta v_c / \Delta v_i)^{1/2},$$

where Δv_i = the velocity range over which the spectrum was integrated, Δv_c = the smoothed channel width, and Δv_b = the velocity range over which the baseline was fitted (see, e.g., Sage & Wrobel 1989). We provisionally consider any result greater than 3σ to be a detection, but note that a line appears to be visible at the $(0, 0)$ position of NGC 1316. More sensitive follow-up observations are necessary for that and several other positions (i.e., NGC 5266 $[-4, -14]$).

3. RESULTS

3.1. The Distribution of Molecular Gas

The distribution of the gas is, in itself, quite unusual. In most early-type (S0) galaxies observed so far, the molecular gas is concentrated toward the center (e.g., Sage & Wrobel 1989; Wiklind & Henkel 1990). In the three galaxies discussed here, the H_2 follows the ionized gas and dust and is *not centrally concentrated*: it is in patches along the galaxy minor axis in NGC 1316, in the nucleus and the spiral-like arms in NGC 1947, and in a ring in NGC 5266 (see Figs. 1–3). The velocities and directions of motion of the CO generally agree with those of the ionized gas, indicating that both phases of the gas coexist. The details are discussed individually below.

3.1.1. NGC 1316

The spectrum obtained from the center of NGC 1316 suggests a detection of CO emission, but the integrated intensity

is only 2σ . However, the velocity range is the same as the sum of the two secure detections, at $(21, -21)$, and $(-12, 48)$. Those detections correspond very well to the distribution of dust sketched by Schweizer (1980) (Fig. 1). At $(-21, 21)$, where the beam overlaps very little of the dust, no CO emission was detected. As in spiral galaxies, the dust and molecular gas appear to be coextensive.

In addition, the CO is rotating in the same sense as the ionized gas. Although Schweizer (1980) did not provide detailed rotation curves, only pictures of the spectra, he does state that the gas is rotating at $\sim -350 \text{ km s}^{-1}$ (with respect to systemic) $35''$ southeast of the center, which corresponds quite well to our $(21, -21)$ position. The centroid of the CO emission at that point is 1520 km s^{-1} , $\sim 100 \text{ km s}^{-1}$ higher than that of the ionized gas. Similarly, $54''$ northwest of the center, Schweizer found the gas moving at $\sim +350 \text{ km s}^{-1}$. In this case, our observed point $(-12, 48)$ is separated by $\sim 28''$, and away from the line of maximum rotation of the ionized gas. The centroid of the CO emission is 1820 km s^{-1} , $\sim 75 \text{ km s}^{-1}$ less than the ionized gas at the same radius, assuming rigid rotation, as suggested by the published spectra (Schweizer 1980). Since the separation between the positions observed at the two wavebands (optical and CO) is fairly large, and the CO pointing is not on the plane of gas rotation, we are not surprised by the difference. Considering the lack of detail provided for the ionized gas, and the extent of the CO beam on the galaxy, we consider the above agreements to be good. The most important point, that the molecular and ionized gas are corotating, is established.

3.1.2. NGC 1947

Unlike the previous case, CO is most strongly detected toward the center of NGC 1947. The agreement between the

centroid of the CO emission (1160 km s^{-1}), and the systemic velocity determined from stars (1174 km s^{-1} , Bertola, Galletta, & Zeilinger 1992) and ionized gas (1180 km s^{-1} , Möllenhoff 1982), is very good. The molecular emission profile (see Fig. 2) has a relatively flat top, unlike many spiral galaxies. The width of the line ($\sim 650 \text{ km s}^{-1}$ full width zero intensity) is greater than anticipated based upon observations of ionized gas where the rotation curve indicates maximum velocities of $\pm 200 \text{ km s}^{-1}$ (Möllenhoff 1982). This difference may be due to noise in the CO data, uncertainty in the optical spectra, or both. Alternatively, the molecular gas may be more spatially extended than the ionized component, and thus trace a greater portion of the galaxy's potential well.

Molecular gas is also seen at the northern (0, 21) position. Dust lanes cross the northern part of NGC 1947, going generally from the northeast to the northwest, again indicating a correspondence between the dust and molecular gas. Since our observed point is relatively far ($\sim 30''$) from the plane of rotation of the ionized gas, a direct comparison of the velocities is not quantitatively meaningful. However, emission-line spectra (Möllenhoff 1982) indicate velocities higher than systemic for gas $\sim 20''$ northwest of the center. The centroid of our northern spectrum is 1200 km s^{-1} , in agreement with the sense of rotation of the ionized gas.

3.1.3. NGC 5266

In this galaxy, CO is clearly detected at the (0, 0) pointing, and at the northern position. The structure of the center profile, with peaks on either side of the systemic velocity and little emission at the centroid, suggests gas distributed in a ring, but is not conclusive in itself. The photograph in Figure 3 clearly shows a dust ring around NGC 5266. Given the usual correspondence between dust and molecular gas, we suggest that the observed CO is primarily associated with this ring. The centroid of the CO line is at 2960 km s^{-1} , close to the 3044 km s^{-1} observed by Varnas et al. (1987) for the stellar component and in very good agreement with the systemic velocity determined for the ionized gas, 2994 km s^{-1} (Varnas et al. 1987). The CO line is asymmetric, with more emission in the low-velocity peak.

The detection of molecular gas at the northern position gives the sense of rotation, and the velocity agrees with that of the ionized gas. The centroid of the CO line at this position is at 2850 km s^{-1} , and the velocity determined from [O III] emission close to the same area is 2834 km s^{-1} . Thus the ionized and molecular gas are clearly corotating.

Although no emission was detected at the southern position, that point had the least amount of integration time in our study. The rms noise in that spectrum is approximately equal to the expected signal, based upon the northern point, so nothing further can be said.

3.2. Total CO Fluxes

The CO line fluxes were calculated differently for each galaxy. For NGC 1316, the detections at (21, -21), (-12, 48), and (0, 0) were used to calculate the flux in a straight sum. Even though there is some beam overlap near the center, the low flux means the potential error incurred by this method is small. If the (0, 0) position is assumed to be undetected, the total flux decreases by $\sim 25\%$, so the maximum error which can be attributed to beam overlap is less than 25%. For NGC 1947 the beam overlap in the observed region is quite significant. In this case, we convolved the four unsmoothed spectra with a Gaussian of HPBW = $65''$, then smoothed and baselined the resultant spectrum in the usual way. The convolution takes the simple-minded approach of weighting each spectrum in the sum according to its distance from the center of the galaxy. This procedure results in a spectrum which is an estimate of what would be measured if the galaxy were observed with a $65''$ beam. Finally, the line flux was determined in the standard way ($I_{\text{CO}} \times$ convolved beam area). This procedure may slightly underestimate the total flux, if there is molecular gas within the area of the $65''$ beam which was not observed in our small map. However, the effect is probably insignificant when compared to the uncertainty in the total H_2 mass. In determining the flux for NGC 5266, we used only the detection at the center position, since the galaxy was essentially contained within the SEST beam (see Fig. 3).

3.3. Molecular Masses

Total molecular masses were estimated from the CO line fluxes using the "standard" conversion factor determined by Solomon et al. (1987) for a sample of virialized clouds within the Milky Way:

$$M(\text{H}_2) = 4.8 L_{\text{CO}} (M_{\odot}). \quad (1)$$

This is equivalent to $N(\text{H}_2) = 3 \times 10^{20} I_{\text{CO}} (\text{cm}^{-2})$. While the standard conversion factor may not be accurate in all individual cases, much recent work suggests that it is a useful indicator of mass within an uncertainty of a factor of 2 or so in a wide range of galaxies (e.g., Young & Sanders 1986; Sage, Shore, &

TABLE 2
THE GAS CONTENT OF MINOR AXIS DUST LANE ELLIPTICALS

NAME	D (Mpc)	GAS CONTENT				TOTAL	
		M_x ($10^8 M_{\odot}$)	$M_{\text{H I}}$ ($10^8 M_{\odot}$)	M_{H_2} ($10^8 M_{\odot}$)	M_{dust} ($10^6 M_{\odot}$)	M_{dyn} ($10^{10} M_{\odot}$)	L_B ($10^{10} L_{\odot}$)
NGC 1316.....	26.3	110	<2	9.5	10	78	20
NGC 5363.....	21.9	5.2	2.2	2.9 ^a	0.76	7.0	2.8
NGC 5128.....	6.3	34	6.0	6.1	4.9	20	14
NGC 1947.....	17.0	<0.77	...	4.2	0.92	6.8	0.90
NGC 5266.....	56.6	...	150	24	5.2	42	9.1

NOTE.—Distances, gaseous masses and galaxy luminosities are from Roberts et al. 1991 except masses of H_2 in NGC 1947, NGC 1316, and NGC 5266, from this paper, and the H I mass for NGC 5128 from Gardner & Whiteoak 1976. Total masses are computed from gas rotation curves, assuming a flat rotation curve with the same maximum velocity observed from emission lines (Graham 1979; Schweizer 1980; Möllenhoff 1982; Sharples et al. 1983; Varnas et al. 1987), and a spatial extent equal to the optical size at 25 mag arcsec $^{-2}$.

^a Calculated using data from Sage & Wrobel 1989.

Solomon 1990; Young & Scoville 1991; Sage & Isbell 1991; Braine & Combes 1992; Sage et al. 1992).

However, it is recognized that the gas physical conditions and CO abundances within the sample galaxies may be substantially different from isolated spirals (see Sage et al. 1992 for a more complete discussion). The masses presented in Table 2 are more likely to be underestimates (because of decreased CO abundance) than overestimates (because the CO is hotter than usual) if the gas were accreted from low-metallicity dwarfs. Other gas origins (i.e., recycled stellar material in the original elliptical) will have other uncertainties. For the purposes of this paper, where we are merely demonstrating the presence of molecular gas in minor axis dust lane ellipticals, and suggesting possible origins, use of a standard conversion factor is sufficient.

In computing the masses, we adopted distances from Roberts et al. (1991). The H_2 masses are summarized in Table 2, where two other minor axis dust lane ellipticals, NGC 5128 and NGC 5363, have been added from Roberts et al. (1991) and Sage & Wrobel (1989), respectively.

4. DISCUSSION

In general, the detection rate for CO in ellipticals is rather low, much less than in S0 or S0/a galaxies (e.g., Gordon 1991; Roberts et al. 1991; Bregman, Hogg, & Roberts 1992). Similarly, the mass of atomic gas in these galaxies is usually low (Knapp 1987; Bregman et al. 1992).

On the contrary, substantial amounts of molecular gas have been detected in all three elliptical galaxies observed by us, with $>10^9 M_\odot$ in NGC 5266. This is an unusual situation when compared to the (relatively few) other elliptical galaxies observed so far, which all have $\lesssim \text{few} \times 10^8 M_\odot$ of H_2 , located primarily at the center (e.g., Gordon 1991). In addition, most of the galaxies discussed here have comparable amounts of molecular and atomic gas (based upon data from the literature), as is true for early-type spirals (e.g., Young & Knezek 1989; Sage 1993).

The lack of cold gas in ellipticals, long known and confirmed by more recent data (see summary by Roberts et al. 1991), has led many authors to conclude that the H I (Knapp 1987; Bregman et al. 1992) and dust (Forbes 1991) found in E galaxies results from the capture of a gas-rich dwarf, or through material stripped from a spiral during a close interaction. A similar conclusion about the origin of the molecular gas has not previously been suggested, possibly due to the small number of ellipticals searched for CO. However, it has been noted that elliptical galaxies have a CO detection rate comparable to that of H I (Bregman et al. 1992).

The capture origin is consistent with the observation that many ellipticals in which H_2 and H I have been detected are, in some way, peculiar. This is particularly true of the galaxies discussed here, where dust lanes and/or rings are always present. If the gas arises from other mechanisms, like cooling flows, then some correlation should exist between the mass of H I and H_2 , and the mass of X-ray gas. Although our sample is small, there is no evidence of any such correlation. Nor is there much evidence for a correlation between the mass of cool gas and the dynamical mass. Again, such a correlation is expected if the cool gas were enriched, primordial hydrogen.

In recent years, it has become evident that some fraction of galaxies are always undergoing interaction events (e.g., Lonsdale, Persson, & Matthews 1984; Joseph & Wright 1985). These interactions, as discussed in the Introduction, can rad-

ically alter the appearance (and energy output) of a galaxy. Today, in addition to the peculiar morphologies of the (ongoing) merging galaxies presented in Arp's atlas, many other features have been recognized as signatures of past mergers: shells, minor axis disks, polar rings, ring galaxies, counterrotating cores, and gas counterrotation (see Whitmore et al. 1990 or Galletta 1991 for a classification).

We will now examine, in greater detail, evidence supporting the view that dust lane elliptical galaxies, and related systems, acquired their H_2 gas through the capture of gas-rich dwarfs.

4.1. The External Origin of the H_2

In all three observed galaxies, the ionized gas is rotating orthogonally to, and faster than, the stars. The irregular dust clouds of NGC 1316 are embedded in a disk of ionized gas rotating at $\sim 350 \text{ km s}^{-1}$ (Schweizer 1980); this disk crosses the stellar component along a plane containing, or close to, the galaxy minor axis. The stellar component rotates with a velocity of $\sim 135 \text{ km s}^{-1}$ along its major axis (Carter 1987). In NGC 1947 many dust lanes parallel to the minor axis are visible (Bertola & Galletta 1978), both near the nucleus and farther out, and emission-line measurements show a rotation velocity of $\sim 200 \text{ km s}^{-1}$ (Möllenhoff 1982) normal to the stellar major axis, where the maximum velocity is 57 km s^{-1} (Bertola et al. 1992). NGC 5266 also shows the gas and stars with orthogonal rotation. The maximum velocities in this galaxy are $\sim 260 \text{ km s}^{-1}$ for the ionized gas and $\sim 210 \text{ km s}^{-1}$ for the stars (Varnas et al. 1987).

These peculiar kinematics, where the rotation velocity of the ionized gas is very different from that of the stars, and perpendicular to the stellar rotation, indicate an external origin for the gas. It is difficult, if not impossible, to envision an evolutionary scenario in which separate components of a primordial galaxy become dynamically decoupled, leaving the capture of an external source of gas as the only plausible explanation.

Other explanations, such as explosive events of gas ejection or tidal interactions with nearby galaxies, pulling primordial gas into orbits orthogonal to the stars, have long been discarded in favor of accretion (see Hawarden et al. 1981; and Schweizer 1983, 1987 for reviews of the first studies on these galaxies). In particular, tidal interactions have been checked for each individual case and must be excluded for many reasons, among which are (1) the lack of companions of significant mass with crossing times shorter than the age of these minor axis disks (many minor axis dust lane galaxies appear isolated, without companions of comparable luminosity), and (2) the fact that the tidal action is more effective in the outer regions of the galaxy, less bound to the nucleus, while these "polar" disks are normal to the galaxy plane in the *inner* regions, and tend to align with it in the *outer* ones. This is contrary to what is expected from tidal torque, which bends the gas plane away from the galaxy's equatorial plane starting from the outside (see the simulations presented by Toomre & Toomre 1972 and Freeman & de Vaucouleurs 1974). In addition, no tidal effect could be invoked to reverse the gas rotation, as observed in the case of gas counterrotating with respect to the stars. A short review of the possible formation mechanisms was presented by Whitmore et al. (1990) for the related polar ring S0's, who concluded that capture of external gas (and stars) is the most plausible origin for these structures.

From our data, the agreement found between the CO and ionized gas velocities indicates that *the molecular component also* arises in the same way as the ionized material, i.e., it is

captured, not primordial. In addition, we can see, through examination of the quantities in Table 2, that the H I and H₂ masses of this type of elliptical galaxy are essentially independent of the current blue luminosity (L_B). This lack of correlation between the cool gas and stellar components is in agreement with the hypothesis that most of the H₂ comes from outside since, within spiral galaxies, there is a correlation (weak, but present; e.g., Sage & Solomon 1989; Young et al. 1989). This latter correlation is generally attributed, like the correlation between FIR and molecular gas, to a causal relationship between the current population of young stars, and the gas out of which they formed. Most evidence so far compiled indicates that the star formation rate is, in a great number of galaxies, simply proportional to the amount of gas (e.g., Sage & Solomon 1989). Sage et al. (1992) recently extended this to a sample of blue compact dwarf galaxies.

Similarly the hot gas, traced by X-rays, seems completely unrelated to the cool (H I and H₂) gas. If the hot halo arises from galaxian winds and is supplied by the population of old stars, there should be no correlation with captured gas. This lack of correlation between cold and hot gas has been already noted in statistical studies on elliptical galaxies (Bregman et al. 1992).

From where was the gas accreted? As stated above, for the galaxies studied here, there are no nearby spirals from which gas could have been stripped. It did not come from the merger of two spirals. A first, violent phase of merging between two galaxies of roughly equal mass may have produced the original elliptical (e.g., Barnes 1989; Hernquist & Barnes 1991), although there is still strong discussion of this point. However, the symmetry of the ionized gas disks and dust, always perpendicular to the galaxy major axis, indicates that such a merger event is *not* responsible for the current dust and cool gas, because violent mergers will typically lack a preferred plane of symmetry. In very special cases, gas and stellar counterrotation could result from a violent merger (Hernquist & Barnes 1991), but this must be exceedingly rare.

In addition, this process of violent merging cannot explain the S0 galaxies with polar rings or gas counterrotation because the structure of these (disk, bulge, ring, etc.) is too complex and fragile to survive an energetic collision. We note here again, as in the Introduction, that the optical morphology and the stellar kinematics of these galaxies are those of normal ellipticals or S0's, so the processes presently active in these systems are qualitatively different from the merging between two equally-sized galaxies, observed in, e.g., IC 4553 (Arp 220), NGC 7252 (Arp 226), and NGC 4038/39 (Arp 244). If the mechanism producing the strong FIR emission detected from some of these galaxies is the same as in our objects (massive stars heating the dust), then the gas mass involved must be very different, since the dust lane ellipticals produce orders of magnitude less FIR.

We conclude that the detected H₂, like the ionized gas and dust, must have been acquired from an external source. Due to a lack of alternatives, we suggest that it came from the accretion of a gas-rich, less massive (dwarf) galaxy.

4.2. Phase Changes in the Accreted Gas

The relatively large quantity of gas detected needs some additional explanation: among dwarfs, only the relatively rare blue compact ones have a mass of H₂ comparable to the masses found for the observed dust lane ellipticals (Sage et al. 1992). However, many other "normal" dwarfs have sufficient

H I to supply the gas mass required to explain the observations, *assuming much of it could be converted to H₂*. In the following, we try to show that the above hypothesis can describe the evolution of these minor axis disks and rings.

Braine & Combes (1993) recently found a systematically higher H₂ mass in perturbed spirals, and suggested that gas infall was the direct cause of this higher H₂ abundance. This result, although obtained for another type of galaxy, nevertheless reinforces our hypothesis. Young & Knezek (1989) also suggested that infall can produce H₂ from the atomic (H I) gas. While this compression is not theoretically well understood, some evidence in favor of such a process exists.

It is not our goal here to identify the precise mechanism. We merely point out that our data agree with the hypotheses made by us and the above authors. Until a better theoretical understanding of the process is developed, we provisionally accept that it is possible to convert H I into H₂ during an interaction or infall event.

4.3. A Scenario for the Evolution of Rings and Disks

Within Tables 2 and 3, the galaxies are arranged in order of regularity of dust lanes, starting from the most chaotic NGC 1316 and proceeding to the smooth and regular NGC 5266. The dust lane in NGC 5128 is morphologically similar to that of NGC 1947, while NGC 5363 still has irregular lanes and patches, like NGC 1316. If the smoothness of the dust ring indicates the age of the phenomenon, as we suggest below, the list of galaxies in Table 2 corresponds to increasing time since the gas accretions.

According to current models, after the gas (and stars) were captured (through absorbing a gas-rich companion) dissipative processes occur which smear the captured material into a disk or annulus, after few orbits around the galaxy (Tubbs 1980; Christodoulou & Tohline 1991; Quinn 1991; Rix & Katz 1991; Steiman-Cameron 1991). The formation of a ring starts, according to different models, ~ 400 Myr (Quinn 1991) or 1.8 Gyr (Rix & Katz 1991) after capture. Disk formation depends on the mass inflow from this ring toward the center, the amplitude of which is a function of the ring's original inclination (with respect to the galaxy equatorial plane) and the shape of the accreting galaxy (see Christodoulou et al. 1992 for a review of the models). After the inclined rings or disks are formed, they settle toward an equilibrium configuration in < 1 Gyr, forming transient warps in their outer regions (Sparke 1986; Steiman-Cameron & Durisen 1988; Steiman-Cameron 1991), similar to what is observed in NGC 5128 and NGC 1947. At the same time the gas cools (Christodoulou et al. 1992; Katz & Rix 1992; Quinn 1991). Cooling inside the ring or flow of gas toward the center both favor local compression processes which could produce the observed H₂ gas, as suggested above.

TABLE 3
COMPARISON OF GLOBAL GAS CONTENTS

Name	$M(\text{H}_2)/M(\text{H I})$	$M_{\text{gas}}/M_{\text{dyn}} (10^{-2})$
NGC 1316.....	> 4.8	< 1.6
NGC 5363.....	1.3	1.5
NGC 5128.....	1.0	2.3
NGC 1947.....	...	≥ 0.73
NGC 5266.....	0.16	≥ 4.1

NOTE.— M_{gas} is the sum of the X-ray, H I, and H₂ components from Table 2.

In support of this, the observed CO distribution seems to follow the optical disk/ring morphology.

If H_2 is concentrated near the nucleus, and interacts with preexisting gas, we have an ideal situation for star formation and subsequent SN explosions², which would then deplete the central regions of gas.

As an aside, we note that if there is no preexisting gas inside the galaxy, or if the infall rate is not sufficient to induce star formation, the gaseous disk could survive for a long time without the formation of a central hole. Also, under certain conditions (high inclination in slightly flattened galaxies), the rings will not collapse to the center within a Hubble time (Quinn 1991; Rix & Katz 1991). In all of these cases, a smooth ring would remain for a long time after the accretion event.

Using the above scenario, the different dust and gas distributions observed in our sample of galaxies can be understood as a consequence of evolution after the accretion: NGC 1316 and NGC 5363 are in the early stages of evolution, with molecular gas and dust in patches, while in NGC 1947 and NGC 5128, the accreted gas has already reached the disk configuration. The smooth and almost regular ring of dust in NGC 5266 suggests an evolved system, where star formation has depleted the central region of the gas disk. Alternatively, the ring may have reached a long-lived configuration without the formation of a disk. A comparison with the theoretical models (Christodoulou et al. 1992; Katz & Rix 1992; Quinn 1991; Steiman-Cameron & Durisen 1988; Steiman-Cameron 1991) indicates that in both cases such a smooth structure should have an age ≥ 4 Gyr.

Further support for this view *could* lie with an interesting trend within Table 3; the monotonic decrease in the $H_2/H\text{I}$ ratio with increasing smoothness. Sage et al. (1992) suggested that, within the blue compact dwarf galaxies, much of the $H\text{I}$ is the *result* of recent star formation activity, where the parent molecular clouds are largely dissociated by UV radiation from the young stars. If we apply a similar explanation to these elliptical galaxies, we can predict that, after the absorption of a dwarf and the subsequent formation of molecular clouds, star formation is triggered. The latter should be able to dissociate the H_2 and deplete the gas. However, given the generally poor

correlation between $H\text{I}$ content and star formation (in spiral galaxies), this must be regarded as very tentative.

One final note concerns the class of related S0's (those with polar rings or counterrotation). Observations of the polar ring galaxy NGC 2685 (Taniguchi et al. 1990) show the nuclear region to be H_2 poor, as is true in NGC 4546 (Sage & Galletta 1993), a galaxy with counterrotating gas and stars. Since dynamical evolution by itself would tend to concentrate gas near the center, because of the dissipative collisions between accreted and preexisting clouds, we suggest that the evolution of the gaseous content, through star formation, must play a role equally as important as the dynamical evolution in determining the final morphology of such systems.

5. CONCLUSIONS

On the basis of the CO observations of three minor axis dust lane galaxies, we have shown that molecular gas which follows the distribution and kinematics of ionized gas has been detected in NGC 1316, 1947, and 5266. The amounts of gas detected are unusually large for ellipticals, $> 4 \times 10^8 M_\odot$.

Based upon dynamical studies of interacting systems, and following related work on the origin of the $H\text{I}$ and ionized gas, we suggest the following:

1. The H_2 comes from gas acquired from an external source, probably through the ingestion of a gas-rich dwarf galaxy.
2. The large quantity of H_2 may be due to mechanisms of gas compression inside the ring into which the accreted object is smeared. These processes may convert $H\text{I}$ into H_2 .

Following the current theoretical models, the three observed galaxies are situated along a possible evolutionary sequence, with NGC 1316 in the earlier stages of gas (or satellite) accretion and NGC 5266 in a smooth, evolved configuration. The distribution of the molecular gas is entirely consistent with the models.

The authors thank G. Fabbiano and H.-W. Rix for useful discussions and suggestions. L. J. S. acknowledges the support of the Max-Planck-Gesellschaft through an MPG fellowship, and the partial support of the North Atlantic Treaty Organization through grant number 910965. G. G. acknowledges partial support through a grant from the Ministry of University and Scientific Research under the program *Astrofisica e Fisica Cosmica*.

REFERENCES

- Barnes, J. E. 1989, *Nature*, 338, 123
 Bertola, F. 1987, in *IAU Symp. 127, Structures and Dynamics of Elliptical Galaxies*, ed. T. de Zeeuw (Dordrecht: Reidel), 135
 Bertola, F., & Galletta, G. 1978, *ApJ*, 226, L115
 Bertola, F., Galletta, G., & Zeilinger, W. W. 1992, *A&A*, 254, 89
 Bettoni, D. 1984, *Messenger*, 37, 17
 Braine, J., & Combes, F. 1992, *A&A*, 264, 433
 ———. 1993, *A&A*, 269, 7
 Bregman, J. N., Hogg, D. E., & Roberts, M. S. 1992, *ApJ*, 387, 484
 Caldwell, N., Kirshner, R. P., & Richstone, D. 1986, *ApJ*, 305, 136
 Christodoulou, D. M., Katz, N., Rix, H.-W., & Habe, A. 1992, *ApJ*, 395, 113
 Christodoulou, D. M., & Tohline, J. E. 1991, in *Warped Disks and Inclined Rings around Galaxies*, ed. S. Casertano, P. D. Sackett, & F. H. Briggs (Cambridge: Cambridge Univ. Press), 122
 Carter, D. 1987, *ApJ*, 312, 514
 Faber, S. M., & Gallagher, J. S. 1976, *ApJ*, 204, 365
 Forbes, D. A. 1991, *MNRAS*, 249, 779
 Freeman, K. C., & de Vaucouleurs, G. 1974, *ApJ*, 194, 569
 Galletta, G. 1987, *ApJ*, 318, 531
 ———. 1991, in *Dynamics of Disc Galaxies*, ed. B. Sundelius (Göteborg: Göteborg Univ.), 317
 Gardner, F. F., & Whiteoak, J. B. 1976, *Proc. Astron. Soc. Australia*, 3, 63
 Graham, J. A. 1979, *ApJ*, 232, 60
 Gordon, M. A. 1991, *ApJ*, 371, 563
 Hawarden, T. G., Elson, R. A. W., Longmore, A. J., Tritton, S. B., & Corwin, H. G., Jr. 1981, *MNRAS*, 196, 747
 Hernquist, L. E., & Barnes, J. E. 1991, *Nature*, 354, 210
 Joseph, R. D., & Wright, G. S. 1985, *MNRAS*, 214, 87
 Katz, N., & Rix, H.-W. 1992, *ApJ*, 389, L55
 Knapp, G. R. 1987, in *IAU Symp. 127, Structure and Dynamics of Elliptical Galaxies* (Dordrecht: Reidel), 145
 Lonsdale, C. J., Persson, S. E., & Matthews, K. 1984, *ApJ*, 287, 95
 Möllenhoff, C. 1982, *A&A*, 108, 130
 Quinn, T. 1991, in *Warped Disks and Inclined Rings around Galaxies*, ed. S. Casertano, P. D. Sackett, & F. H. Briggs (Cambridge: Cambridge Univ. Press), 143
 Rix, H.-W., & Katz, N. 1991, in *Warped Disks and Inclined Rings around Galaxies*, ed. S. Casertano, P. D. Sackett, & F. H. Briggs (Cambridge: Cambridge Univ. Press), 112
 Roberts, M. S., Hogg, D. E., Bregman, J. N., Forman, W. R., & Jones, C. 1991, *ApJS*, 75, 751
 Sage, L. J. 1993, *A&A*, 272, 123
 Sage, L. J., & Galletta, G. 1993, *ApJ*, submitted
 Sage, L. J., & Isbell, D. W. 1991, *A&A*, 247, 320

- Sage, L. J., Salzer, J. J., Loose, H.-H., & Henkel, C. 1992, *A&A*, 265, 19
- Sage, L. J., Shore, S. N., & Solomon, P. M. 1990, *ApJ*, 351, 422
- Sage, L. J., & Solomon, P. M. 1989, *ApJ*, 342, L15
- Sage, L. J., & Wrobel, J. M. 1989, *ApJ*, 344, 204
- Schweizer, F. 1980, *ApJ*, 237, 303
- . 1983, in *IAU Symp. 100, International Kinematics and Dynamics of Galaxies*, ed. E. Athanassoula (Dordrecht: Reidel), 321
- . 1987, in *IAU Symp. 127, Structure and Dynamics of Elliptical Galaxies*, ed. T. de Zeeuw (Dordrecht: Reidel), 118
- Schweizer, F., Whitmore, B. C., & Rubin, V. C. 1983, *AJ*, 88, 909
- Scoville, N. Z. 1991, in *IAU Symp. 146, Dynamics of Galaxies and Molecular Cloud Distribution*, ed. F. Combes & F. Casoli (Dordrecht: Kluwer), 315
- Sharples, R. M., Carter, D., Hawarden, T. G., & Longmore, A. J. 1983, *MNRAS*, 202, 37
- Solomon, P. M., Rivolo, A. R., Barrett, J. W., & Yahil, A. 1987, *ApJ*, 319, 730
- Sparke, L. S. 1986, *MNRAS*, 219, 657
- Steiman-Cameron, T. Y. 1991, in *Warped Disks and Inclined Rings around Galaxies*, ed. S. Casertano, P. D. Sackett, & F. H. Briggs (Cambridge: Cambridge Univ. Press), 131
- Steiman-Cameron, T. Y., & Durisen, R. H. 1988, *ApJ*, 325, 26
- Taniguchi, Y., Sofue, Y., Wakamtsu, K.-I., & Nakai, N. 1990, *AJ*, 100, 1086
- Toomre, A., & Toomre, J. 1972, *ApJ*, 178, 623
- Tubbs, A. D. 1980, *ApJ*, 241, 969
- Varnas, S., Bertola, F., Galletta, G., Freeman, K. C., & Carter, D. 1987, *ApJ*, 313, 69
- Whitmore, B. C., Lucas, R. A., McElroy, D. B., Steiman-Cameron, T. Y., Sackett, P. D., & Olling, R. B. 1990, *AJ*, 100, 1489
- Wiklund, T., & Henkel, C. 1990, *A&A*, 227, 394
- Young, J. S., & Knezek, P. M. 1989, *ApJ*, 347, L55
- Young, J. S., & Sanders, D. B. 1986, *ApJ*, 302, 680
- Young, J. S., & Scoville, N. Z. 1991, *ARA&A*, 29, 581
- Young, J. S., Xie, S., Kenney, J. D. P., & Rice, W. L. 1989, *ApJS*, 70, 699