MOLECULAR GAS IN ELLIPTICAL GALAXIES: DISTRIBUTION AND KINEMATICS

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ABSTRACT

I present interferometric images (~7″ resolution) of CO emission in five elliptical galaxies and nondetections in two others. These data double the number of elliptical galaxies whose CO emission has been fully mapped. The sample galaxies have $10^8$ to $5 \times 10^9 M_\odot$ of molecular gas distributed in mostly symmetric rotating disks with diameters of 2–12 kpc. Four out of the five molecular disks show remarkable alignment with the optical major axes of their host galaxies. The molecular masses are a few percent of the total dynamical masses that are implied if the gas is on circular orbits. If the molecular gas forms stars, it will make rotationally supported stellar disks that will be very similar in character to the stellar disks now known to be present in many ellipticals. Comparison of stellar kinematics to gas kinematics in NGC 4476 implies that the molecular gas did not come from internal stellar mass loss because the specific angular momentum of the gas is about 3 times larger than that of the stars.

Key words: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: individual (UGC 1503, NGC 807, NGC 3656, NGC 4476, NGC 5666, NGC 4649, NGC 7468) — galaxies: ISM — galaxies: kinematics and dynamics — ISM: molecules

1. INTRODUCTION

It is now well known that elliptical galaxies often do have interstellar media with some cold neutral gas and dust. Huchtmeier, Sage, & Henkel (1995) have found that about two-thirds of ellipticals in the Revised Shapley-Ames (RSA) catalog contain H I at levels $M$(H I)/$L_B \gtrsim 10^{-3}$ in solar units; Wardle & Knapp (1986) reach similar conclusions. Colbert, Mulchaey, & Zabludoff (2001) find that dust is apparent in optical images of about 75% of all ellipticals regardless of their environment (field vs. X-ray–detected poor groups). The molecular gas content of ellipticals is more difficult to quantify because, with few exceptions, only the ones that are bright in the far-infrared (FIR) have been searched. However, Knapp & Rupen (1996) quote CO detection rates of 20%–80% for ellipticals that are brighter than 1 Jy at 100 μm.

Since it was believed for many years that elliptical galaxies have little or no cold molecular gas, detailed studies of that molecular gas can offer fundamental insight into the evolution of ellipticals. For example, one would obviously like to know the origin of the molecular gas. Did it come from internal sources (stellar mass loss) or from an external source (another galaxy)? Has it been there for a Hubble time or significantly less? The distribution and kinematics of the molecular gas, and particularly comparisons of the specific angular momentum of the gas and the stars, can help clarify the origin of the molecular gas. Molecular gas is also the raw material for star formation. Therefore, the properties of the molecular gas determine where and how much star formation can happen; this determines the future morphology of the galaxy. Finally, molecular gas distribution and kinematics are valuable because the dissipational nature of gas means that the shapes of the gas orbits are much better known than are the stellar orbits (e.g., de Zeeuw & Franx 1989; Cretton, Rix, & de Zeeuw 2000). Ga kinematics can be used to infer the galaxy potential in a way that is more robust than, or at least complementary to, what one can do with stellar kinematics. This paper uses high-resolution CO observations to investigate these ideas about elliptical galaxy structure and evolution.

Several authors have used single-dish telescopes to search for CO emission from ellipticals. The largest of these works are Lees et al. (1991), Wiklind, Combes, & Henkel (1995, hereafter WCH95), and Knapp & Rupen (1996). A very small number of elliptical galaxies have been mapped in CO with millimeter interferometers or with multiple pointings on single-dish telescopes. These include NGC 759 (Wiklind et al. 1997), NGC 1275 (Reuter et al. 1993; Braine et al. 1995; Inoue et al. 1996), NGC 7252 (Wang, Schweizer, & Scoville 1992), NGC 1316 (Horellou et al. 2001), and NGC 5128 = Cen A (Quillen et al. 1992; Rydbeck et al. 1993; Charmandaris, Combes, & van der Hulst 2000). In all of these galaxies except NGC 7252, molecular gas is found in a rotating disk on the order of a kpc or a few kpc in radius and containing about $10^9 M_\odot$ of H$_2$. In Cen A, a nearby galaxy which permits detailed observations, the large scale CO disk closely follows the prominent optical dust lane and is strongly warped (Quillen et al. 1992). About 10% of the CO in Cen A is associated with stellar and H I shells at galactocentric radii of 15 kpc (Charmandaris et al. 2000). The CO in NGC 7252, a merger remnant, has compact but irregular structure and kinematics.

The present paper doubles the number of elliptical galaxies with CO maps; I show images of CO emission in five elliptical galaxies and nondetections in two others. In addition, the present sample is valuable because it employs a clearly defined set of selection criteria (in contrast to the semirandom collection of interesting galaxies mentioned above).

2. SAMPLE SELECTION

The observed galaxies were chosen from a survey of CO emission in ellipticals that was made with the IRAM 30 m telescope by WCH95. WCH95, Lees et al. (1991), Gordon (1991), Sage & Wrobel (1989), Knapp & Rupen (1996), and several other sets of authors selected galaxies for single-dish
CO surveys based on a combination of IRAS 60 µm and 100 µm fluxes and galaxy type. The most common FIR flux criterion (used by WCH95 and all of the surveys mentioned here except Sage & Wrobel 1989) is $S_{100,\mu m} > 1.0$ Jy, where the 100 µm fluxes were taken from the compilation of Knapp et al. (1989). WCH95 attempted to pick out “genuine” ellipticals by restricting their sample to galaxies known to have an $r^{1/4}$ profile or, in their words, “a consistent classification as E in several catalogs.” Those criteria defined a sample of 29 ellipticals, of which 16 were detected in CO.

The present sample contains all but one of the galaxies that were detected by WCH95 with $^{12}$CO 1−0 integrated intensities greater than 5.0 K km s$^{-1}$ (23 Jy km s$^{-1}$) and that lie within the declination range accessible to the Berkeley-Illinois-Maryland Association (BIMA) telescopes and the Owens Valley Radio Observatory (OVRO). NGC 759, which also meets these criteria, was excluded because a high-resolution CO map of this galaxy has already been published (Wiklind et al. 1997). To this list I also added NGC 4649, for which a CO detection is reported by Sage & Wrobel (1989). The resulting sample is given in Table 1.

There is significant overlap between the sample selected here from the survey of WCH95 and other single-dish CO surveys. NGC 5666 and NGC 4476 have the second- and third-highest CO 2−1 intensities in the sample of 24 galaxies studied by Lees et al. (1991). NGC 5666 has the highest CO 2−1 intensity in the sample of seven ellipticals studied by Gordon (1991).

The galaxies observed by WCH95 are found almost evenly divided among the field, groups, and clusters. Of the galaxies observed here, three are classified by WCH95 as being field ellipticals, one is a member of a small group, two are in the Virgo cluster, and one is most likely a merger remnant. If molecular gas is associated with dust, then this distribution of environments is consistent with the study of Colbert et al. (2001), who found that optical signatures of dust are found in field ellipticals at the same rate as in ellipticals in X-ray–bright groups. Additional discussion of selection effects in the present sample can be found in § 5.5.

3. OBSERVATIONS AND DATA REDUCTION

3.1. BIMA Data

Six galaxies (UGC 1503, NGC 807, NGC 3656, NGC 4476, NGC 4649, and NGC 5666) were observed with the ten-element Berkeley-Illinois-Maryland Association (BIMA) millimeter interferometer at Hat Creek, CA (Welch et al. 1996). The BIMA observations were carried out in the C configuration (projected baselines 3−34 kλ) between 1998 November and 2001 June. One additional track in the D configuration was obtained for NGC 5666 in 1999 March, giving projected baselines down to 2.3 kλ for that galaxy.

Each galaxy was observed with a single pointing centered on the optical center of the galaxy; the primary beam FWHM is about 100″. Each observation covered a velocity range of about 1000 km s$^{-1}$ centered on the velocity of the CO detected by WCH95. The optical velocities of the galaxies are uncertain by up to 100 km s$^{-1}$, but are always well within the velocity range covered. Table 1 gives some basic data for the sample galaxies, and Table 2 summarizes important parameters of the observations and the final images.

Reduction of the BIMA data was carried out using standard tasks in the MIRIAD package (Sault, Teuben, & Wright 1995). Electrical line length calibration was applied to most of the tracks, with a few exceptions in cases where the measurement was too noisy to be useful or where the line length was a very smooth function of time. Data from an atmospheric phase monitor (Lay 1999) were used to estimate the magnitude of amplitude decorrelation, as described by Regan et al. (2001) and Wong (2001). A small interferometer with a fixed 100 m baseline measures the rms path length difference in the signal from a commercial broadcast satellite; those data are scaled to the observing frequency and are scaled by projected baseline length raised to the 5/6 power to estimate the amount of amplitude decorrelation in the data (Akeson 1998). An rms path length difference of 300 µm on a 100 m baseline produces an amplitude decorrelation of 0.82 for observations at 3 mm wavelength (Akeson 1998), but the longest baseline in the present data is 88 m. Twelve tracks with rms path lengths less than 300 µm were not explicitly corrected for decorrelation because normal amplitude calibration can take out most of the decorrelation effect (Wong 2001). Fourteen tracks with rms path lengths in the range 300−700 µm were corrected using the MIRIAD task $wdecor$, which multiplies up the data ampli-

![Table 1: Sample Galaxies](http://bima.astro.umd.edu/memo/memo.html)
tudes to correct for decorrelation losses and decreases the weights of data with large decorrelation losses. Data with rms path lengths larger than 700 $\mu$m were generally not used. The worst track that was used had a median amplitude correction factor of 1.15. Amplitude corrections were applied to all observed sources and calibrators before the correction factor of 1.15. Amplitude corrections were used. The worst track that was used had a median amplitude of 10% or less in amplitude and 2.3C 273 indicate that residual passband variations are on the order of frequency were corrected by the on-drifts as a function of time were corrected by means of a monomet, which is usually monitored several times per month (see Table 2). Phase I used the secondary calibrator, 3C 273, which is usually applied to all observed sources and calibrators before the correction factor of 1.15. Amplitude corrections were made.

Absolute flux calibration was based on observations of Uranus or Mars. When suitable planets were not available, I used the secondary calibrator, 3C 273, which is usually monitored several times per month (see Table 2). Phase drifts as a function of time were corrected by means of a nearby calibrator observed every 30–40 minutes. Gain variations as a function of frequency were corrected by the online passband calibration system; inspection of the data for 3C 273 indicate that residual passband variations are on the order of 10% or less in amplitude and 2° in phase across the entire band.

The calibrated visibility data were weighted by the inverse square of the system temperature and the inverse square of the rms path lengths larger than 700 $\mu$m. Data with large decorrelation losses. Data with rms path lengths larger than 700 $\mu$m were generally not used. The worst track that was used had a median amplitude correction factor of 1.15. Amplitude corrections were applied to all observed sources and calibrators before the correction factor of 1.15. Amplitude corrections were used. The worst track that was used had a median amplitude of 10% or less in amplitude.

The calibrated visibility data were weighted by the inverse square of the system temperature and the inverse square of the amplitude decorrelation correction factor, then Fourier transformed. No continuum emission was evident in the line-free channels of any galaxy (Table 3). The dirty images were lightly deconvolved with the Clark clean algorithm, as appropriate for these compact, rather low signal-to-noise ratio detections. Integrated intensity and velocity field maps were produced by the masking method: the deconvolved image cube was smoothed along both spatial and velocity axes, and the smoothed cube was clipped at about 2.5 $\sigma$ in absolute value. The clipped version of the cube was used as a mask to define a three-dimensional volume in which the emission is integrated over velocity. This masking method is described in greater detail by Wong (2001) and Regan et al. (2001).

### 3.2. OVRO Data

One galaxy, NGC 7468, was observed with the six-element OVRO millimeter interferometer (Padin et al. 1991). Those data were obtained in the C, L, and E configurations (projected baselines 4–44 k$\lambda$) during 2001 April and May. A single pointing was made on the optical center of the galaxy; the primary beam FWHM was about 65". The correlator was set up with four modules of 32 channels, each channel 4 MHz wide; the modules were overlapped to cover a total bandwidth of 464 MHz. The data were calibrated using the MMA package (Scoville et al. 1993). Absolute flux calibration was based on observations of Uranus; the passband and time-dependent phase calibration used the nearby source 3C 454.3. The calibrated data were mapped in AIPS using “natural” weighting. Subsequent image analysis was identical to that for the BIMA data.

### 4. RESULTS

#### 4.1. Non detections

No CO emission was detected in the data cubes for NGC 4649 or NGC 7468. Upper limits to the CO fluxes from these galaxies were determined by first summing the data cube over a square region 22.5" on a side, centered on the optical center of the galaxy, to produce a spectrum. The 22.5" region was chosen to be similar in size and area to the beam of the IRAM 30 m telescope. A spectrum was also produced for a 55" square region (similar to the area of the NRAO 12 m telescope) for NGC 4649. Nothing but noise is apparent in the spectra (Figs. 1 and 2). The spectra were then summed over the velocity ranges described below. The uncertainty in the sum is calculated from the rms in the spectrum and the number of channels summed, as described by Young (2000) and Lees et al. (1991); 3 $\sigma$ limits are given in Table 4. This estimate assumes the channels are uncorrelated, which is an

| Galaxy   | Observation Dates | Flux Calibrator | Velocity Range (km s$^{-1}$) | Beam (arcsec) | Channel (km s$^{-1}$) | Noise (mJy beam$^{-1}$) |
|----------|-------------------|----------------|-----------------------------|--------------|----------------------|------------------------|
| UGC 1503 | 2000 Nov–2001 Jun | Uranus         | 4530–5580                   | 7.10 × 2.1   | 30                   | 8.5                    |
| NGC 807  | 2000 Dec–2001 May | Uranus         | 4230–5280                   | 7.00 × 6.34  | 30                   | 8.0                    |
| NGC 3656 | 2000 Mar, Apr    | 3C 273         | 2375–3335                   | 7.76 × 6.16  | 30                   | 16                     |
| NGC 4476 | 2000 Mar, Apr    | 3C 273/Saturn  | 1480–2440                   | 8.29 × 5.66  | 30                   | 11                     |
| NGC 4649 | 2000 May         | 3C 273         | 450–1800                    | 8.22 × 6.07  | 30                   | 24                     |
| NGC 5666 | 1998 Nov–1999 Apr| Mars/3C 279    | 1865–2555                   | 10.32 × 7.63 | 30                   | 15                     |
| NGC 7468 | 2001 Apr, May    | Uranus/3C 454.3| 1628–2772                   | 6.54 × 5.45  | 30                   | 17                     |

**Note:**—Continuum images were made by averaging all of the line-free channels in the final image cubes. The values quoted here are 3 times the rms noise in the continuum images, so they should be interpreted as flux density limits for point sources at the centers of their host galaxies.
excellent assumption for these data, since no baseline or continuum emission needs to be subtracted.

WCH95 reported a detection, which they characterize as tentative, of 6.7 K km s$^{-1}$ $\sim$ 31 Jy km s$^{-1}$ in the $^{12}$CO 1–0 line from NGC 7468. Their line is centered at 2300 km s$^{-1}$ (220 km s$^{-1}$ distant from the optical velocity) and 665 km s$^{-1}$ wide. The present OVRO observations give a sum of 4.7 ± 2.9 Jy km s$^{-1}$ over the 22.5 square region and over the same velocity range as the CO line of WCH95. The OVRO data also give a sum of 3.6 ± 2.0 Jy km s$^{-1}$ over the same spatial region but over a 300 km s$^{-1}$ velocity range centered on the H$\text{I}$ velocity. (The H$\text{I}$ line in NGC 7468 is about 200 km s$^{-1}$ wide at 20% of peak intensity; see van Driel et al. 2000.) Emission as strong as that reported by WCH95 should have been easily detected. I also consider it unlikely that CO in NGC 7468 is invisible to the interferometer by virtue of being smoothly distributed; the 23$''$ beam of the 30 m telescope is only 3 times larger than the 7$''$ beam of the OVRO data, so the relevant spatial scales are well sampled in the interferometer data.

Thus, the OVRO data for NGC 7468 confirm the nondetection of the 2–1 line of CO by Lees et al. (1991). Those authors quote an upper limit H$_2$ mass of $8 \times 10^7$ $M_\odot$ (after scaling to the conversion factor and distance assumed here), which is consistent with the present $6 \times 10^7$ $M_\odot$ limit. Details of the H$_2$ mass estimates are described in § 4.2.

Sage & Wrobel (1989) report the detection of 18.7 ± 2.3 Jy km s$^{-1}$ of emission in $^{12}$CO 1–0 from NGC 4649. Those observations were made with the NRAO 12 m telescope, which has a beam of 55$''$; the reported line is 225 km s$^{-1}$ wide. The detection is not considered tentative, but again there is a rather large offset (200 km s$^{-1}$) between the CO velocity and the optical velocity. A sum over a 55$''$ box and over the same velocity range noted by Sage & Wrobel (1989) gives an integrated flux of 33 ± 18 Jy km s$^{-1}$ in the present images. A sum of the BIMA data over a 22.5$''$ box and over a 300 km s$^{-1}$ range centered on the optical velocity of the galaxy gives an integrated flux of 5.6 ± 6.0 Jy km s$^{-1}$. If the CO detected by Sage & Wrobel (1989) was smoothly distributed over the 225 km s$^{-1}$ velocity range and over the 55$''$ beam of the 12 m telescope, it would be too faint to be detectable in the current interferometer images. Furthermore, it would be invisible to the interferometer, which does not sample those 55$''$ spatial scales. If, however, the CO detected by Sage & Wrobel (1989) was concentrated within one 8$''$ × 6$''$ beam for each individual channel, it would have

\begin{table} 
\centering 
\caption{H$_2$ Mass and Morphology} 
\begin{tabular}{|l|c|c|c|c|c|c|c|}
\hline
\text{Galaxy} & \text{CO Flux} & \text{$M(H_2)$} & \text{CO Diameter} & \text{CO Shape} & \text{P.A.} & \text{Axis P.A.} \\
& \text{(Jy km s$^{-1}$)} & \text{(10$^8$ $M_\odot$)} & \text{(arcsec)} & \text{(kpc)} & \text{(deg)} & \text{(deg)} \\
\hline
UGC 1503 & 32 (6) & 18 & 30 & 11 (1) & 0.37 (0.05) & -111 (1) & -123 (2) \\
NGC 807 & 29 (6) & 14 & 40 & 12 (1) & 0.58 (0.09) & 143 (1) & 149 (3) \\
NGC 3656 & 200 (20) & 47 & 34 & 7.4 (0.7) & 0.73 (0.02) & 174.8 (0.1) & 191 (3) \\
NGC 4476 & 30 (3) & 1.1 & 27 & 2.4 (0.2) & 0.57 (0.04) & -151 (1) & -152 (1) \\
NGC 4649 & $<18$ & $<0.68$ & ... & ... & ... & ... & ... \\
NGC 5666 & 39 (4) & 5.7 & 28 & 4.7 (0.5) & 0.11 (0.06) & 166 (5) & 165 (2) \\
NGC 7468 & $<6.2$ & $<0.57$ & ... & ... & ... & ... & ... \\
\hline
\end{tabular}
\end{table}

Note.—Upper limits are 3 $\sigma$ for a 22.5$''$ × 22.5$''$ region and 300 km s$^{-1}$ velocity range. See text for further information. Ellipticities and position angles (both morphological and kinematic) for the CO distributions are the median values from fits to three or four images made at different resolutions or with different clip levels. The values in parentheses for these last three columns are estimates of the uncertainty based on the spread among the different fits, because those spreads are always larger than the formal uncertainties of the fits. Position angles are measured north through east to the receding major axis.
been detectable at the 4–8σ level. Additional mosaic observations of NGC 4649 in BIMA’s D configuration have better sensitivity to large-scale structures; those observations will be reported in a future paper, and they also fail to detect CO in NGC 4649.

4.2. CO Fluxes and \( \text{H}_2 \) Masses

For the galaxies with CO detections, Figures 3–7 show images of the integrated CO intensity, individual channel maps, velocity fields, spectra, and position-velocity diagrams along the major axis. Total fluxes were measured from the integrated intensity images in Figures 3a, 4a, 5a, 6a, and 7a. The uncertainties in the CO fluxes are probably 10% for the stronger detections (NGC 3656, NGC 4476, and NGC 5666), dominated mostly by the absolute calibration. For NGC 807 and UGC 1503 the uncertainty is probably a bit larger, perhaps 15%–20%, because of uncertainties in the absolute calibration and in choosing the spatial region to be summed.

The CO fluxes measured in the present images of UGC 1503, NGC 807, and NGC 4476 are consistent within 20% of the \( ^{12}\text{CO} \) 1–0 fluxes measured by WCH95 using the IRAM 30 m telescope. WCH95 detected a larger CO flux from NGC 5666, 60 Jy km s\(^{-1}\), than I find in the BIMA image (40 Jy km s\(^{-1}\)). The difference is nominally larger than the combined uncertainties, which are about 10% for the BIMA image and probably 10%–15% for the data of WCH95 (C. Henkel 2002, private communication).

However, there is no compelling evidence that the interferometer has missed a significant component of the molec-
ular gas in this galaxy. Conversely, the images shown here reveal that the molecular gas distributions for UGC 1503, NGC 4476, and NGC 5666 are not very much larger than the 23'' (FWHM) beam of the 30 m telescope, so there is no compelling evidence that the single-dish spectra missed significant components of the molecular gas in these galaxies. The exception to this latter statement is NGC 3656, which has a factor of 2 larger flux in the BIMA images than in the spectrum of WCH95; most likely this is because the gas distribution is larger than the 30 m beam. The CO line widths agree well in all cases.

H$_2$ masses (Table 4) are calculated using the distances in Table 1 and a “standard” H$_2$/CO conversion factor of $3.0 \times 10^{20}$ cm$^{-2}$(K km s$^{-1}$)$^{-1}$, as in WCH95. With this conversion factor, H$_2$ masses are related to CO fluxes $S_{CO}$ by $M(H_2) = (1.18 \times 10^4 \ M_\odot) D^2 S_{CO}$, where $D$ is the distance in Mpc and $S_{CO}$ is the CO flux in Jy km s$^{-1}$. No correction has been made for the presence of helium.
4.3. CO Morphology

Figures 3a, 3b, 4a, 4b, 5a, 5b, 6a, 6b, 7a, and 7b show integrated CO intensity maps and channel maps for the five galaxies with detected CO emission. The molecular gas in these five elliptical galaxies is found in very regular, symmetric rotating disks with diameters of a few up to 12 kpc. The disks appear flat at the current resolution and sensitivity; the only feature that can be reliably identified outside of the flat disks is in NGC 3656 (Fig. 5a). In this galaxy, the majority of the molecular gas is found in a disk oriented north-south, following the optical dust lane (Balcells et al. 2001).

Roughly 6% of the galaxy’s total CO flux comes from a feature at 11h23m40s, 53°50′20″ (J2000), about 10″ west of the southern end of the main CO disk. The feature is also visible in the individual channel images (Fig. 5b) near 2975 km s⁻¹. The features above and below the disk of NGC 807 (Fig. 4a) may simply be noise.

With the current rather low resolution it is difficult to be sure whether the elongated molecular gas distributions come from disks or bars. I assume in the majority of this paper that they are disks because of the characteristic “butterfly” pattern, which is apparent in the channel maps for UGC 1503, NGC 807, and NGC 4476 (Figs. 3b, 4b, and 6b).
In this pattern, the channels near to the systemic velocity show gas distributions that are elongated in the direction of the kinematic minor axis, but the edge channels show much more compact gas distributions. This pattern is characteristic of roughly circular gas disks inclined to the line of sight. NGC 807 and UGC 1503 also show rotation curves that rise and then flatten in the manner common to spiral galaxy gas disks (\textsuperscript{x}4.4). The butterfly pattern is not obvious in the channel maps for NGC 3656 (Fig. 5\textsuperscript{b}); I continue to assume that the gas is in a disk rather than a bar, but higher resolution observations would be beneficial.

Two of the galaxies show evidence for asymmetries in their gas distributions (the CO emission is stronger on one side than the other). This effect is dramatic for NGC 807 (Fig. 4\textsuperscript{a}), where approximately 30\% of the CO emission comes from the northwest half of the galaxy and 70\% from the southeast half. The asymmetry is also apparent in the channel maps of Figure 4\textsuperscript{b}, where the peak intensity in the channel at 4880 km s\textsuperscript{-1} is 10 \(\sigma\) but the peak intensity in the matching channels on the other side of the systemic velocity (4430 and 4480 km s\textsuperscript{-1}) is only 5 \(\sigma\). Such a large intensity difference is unlikely to be due to noise. WCH95’s spectrum of NGC 807 does not show the high-velocity side to be stronger than the low-velocity side, but this is probably because the peak intensity in the 4880 km s\textsuperscript{-1} channel occurs 10\" away from the galaxy center (see also Fig. 4\textsuperscript{c}). This means that the strongest emission in the galaxy comes from regions at the half-power point of the IRAM 30 m telescope beam, and the 30 m telescope has much less sensitivity to this feature than the interferometer. A lopsided CO distribution is
also evident in NGC 4476 (Fig. 6a), although to a lesser extent.

None of the galaxies show definitive evidence for CO at large radii as in Cen A (Charmandaris et al. 2000). In that galaxy, at least 10% of the CO emission of the galaxy is not associated with the optical dust lane but is found in stellar shells at 15 kpc radius. The rms noise levels in the images (Table 2) are such that an unresolved source appearing in one channel at the 5 $\sigma$ level would have a CO flux of 1–2 Jy km s$^{-1}$, which is less than 10% of the CO fluxes of all of the galaxies detected here (Table 4). Thus, if 10% of the CO emission were in features like those of Cen A it would most likely have been detected. The numbers are particularly compelling for NGC 3656 (the galaxy that, optically, looks most disturbed). Molecular gas associated with the optical shell and containing as little as 1% of the total CO flux of that galaxy would probably have been detected. Thus, the present images suggest that Cen A is unique or at least unusual in having such large quantities of molecular gas associated with its shells.
In order to quantify the axis ratios and position angles of the CO distributions, the integrated intensity maps were fitted with elliptical Gaussians. The ellipticity and position angle of the fitted Gaussians are given in Table 4 along with estimates of the maximum detected extent of the CO.

4.4. CO Kinematics

Initial kinematic analysis of the molecular gas was performed by fitting simple solid body rotation profiles to the velocity fields in Figures 3c, 4c, 5c, 6c, and 7c. NGC 807 and UGC 1503 were also fitted with profiles that rise in their inner parts and then flatten. None of these fits constrain the disk inclination angles \( i \) or maximum rotation velocity particularly well; the product \( V \sin i \) is better constrained. But this procedure does give good estimates of the position angle of the kinematic major axis (Table 4), which were used for the position-velocity plots in Figures 3e, 4e, 5e, 6e, and 7e. Since the fits are weighted by the integrated intensity, the fitted angle is really the kinematic major axis at small radii. The only case in which the major axis clearly varies with radius is NGC 3656, which is described in more detail below.

In one case (NGC 3656) there is a dramatic misalignment of nearly \( 17^\circ \) between the two angles in Table 4, much larger than the combined errors of the fits. This misalignment is clearly visible in Figure 5c from the fact that the kinematic minor axis (the isovelocity curve at the systemic velocity) is not perpendicular to the kinematic major axis at large radii or to the morphological major axis. However, the kinematic major axis at large radii does appear to be closely aligned with the morphological major axis. Thus, the molecular gas...
in NGC 3656 is either in a warped disk or is on elliptical orbits in a nonaxisymmetric potential (Binney & Merrifield 1998, pp. 513, 713–715). Optical images of this galaxy clearly show an S-shaped dust lane (e.g., Balcells et al. 2001), in which the twist of the dust lane is in exactly the sense needed to explain the twist in the CO kinematic major axis, so the CO probably follows the warped dust lane.

The remaining two cases (NGC 807 and UGC 1503) show moderate misalignments of 6° and 12° between the CO morphological and kinematic major axes. These misalignments are nominally greater than the uncertainties in the fits, but they are probably not reliable. These are the two galaxies for which the morphological position angles are the most questionable because the integrated intensity contours are the least elliptical.

The position-velocity diagrams show steeply rising, approximately solid body rotation regions in the center of each galaxy. In NGC 4476 and NGC 5666 the CO does not extend past the region of solid body rotation, which is at least 3–4 beams across. In NGC 3656 there are some signs that the CO rotation curve flattens near the edges of the CO distribution; note in particular the low-velocity side of the position-velocity diagram (Fig. 5e) and the velocity field (Fig. 5c). In NGC 807 and UGC 1503 (the most luminous...
galaxies of the sample, with the largest CO disk linear sizes) the rotation curve clearly turns over and becomes flat at radii of approximately 2.0 kpc (NGC 807) and 1.4 kpc (UGC 1503).

For these latter two galaxies whose rotation curves turn over, the kinematic centers of the gas are coincident with the optical centers of the galaxies (Cotton, Condon, & Arbizani 1999) within an arcsecond or so (10% of the beam). For NGC 4476, NGC 3656, and NGC 5666 the kinematic centers are not well constrained, but the morphological centers of the molecular gas disks are closely coincident with the optical centers.
4.5. Dynamical Masses

These interferometric observations provide two important pieces of information that are missing from single-dish CO surveys of ellipticals: the linear sizes and axial ratios of the molecular disks. If the disks are assumed to be intrinsically circular, with gas on circular orbits, the inclination angle of the disk is given by

$$i = \cos^{-1}\left(\frac{b}{a}\right)$$

where $b/a$ is the minor/major axis length ratio and the equality is achieved only in the limit that the disk is very thin. The observed gas velocities can then be used to calculate the dynamical mass interior to the disk’s outer edge:

$$M_{\text{dyn}} = (2.33 \times 10^5 \, M_\odot) V^2 R,$$

where $R$ is the radius of the outer edge in kpc and $V$ is the observed velocity in km s$^{-1}$, corrected for inclination. The implied dynamical masses (Table 5) range from a few $\times 10^9 \, M_\odot$ to nearly $10^{11} \, M_\odot$ interior to the edge of the CO disk, and the observed masses of molecular gas are a few percent of these dynamical masses. Table 5 also gives the orbital time for gas at the edges of the CO disks.

Fig. 6 — NGC 4476. (a) Molecular gas. Heavy white contours show the CO integrated intensity in units of $-20\%, -10\%, 10\%, 20\%, 30\%, 50\%, 70\%$, and $90\%$ of the peak ($12.4 \, \text{Jy beam}^{-1} \, \text{km s}^{-1} = 7.3 \times 10^{21} \, \text{cm}^{-2}$). Other features as in Fig. 3a. (b) Individual channel maps showing CO emission. As for Fig. 3b, but the contour levels are multiplied by $1 \sigma = 11.5 \, \text{mJy beam}^{-1}$. The cross marks the morphological center of the gas, which is coincident with the optical center of the galaxy to about $2''$. (c) Velocity field. The CO intensity-weighted mean velocity (moment 1) is shown in gray scale and in contours from 1860 to 2040 km s$^{-1}$ in steps of 20 km s$^{-1}$. The ellipse shows the beam size. (d) CO spectrum, constructed in the same manner as for Fig. 3d. (e) Position-velocity diagram. This slice is centered on the morphological center of the molecular gas (R.A. 12h29m59s, decl. +12°54'2", J2000) and follows the kinematic major axis at $-152°$. Contour levels are $-15\%, 15\%, 30\%, 50\%, 70\%$, and $90\%$ of $125.1 \, \text{mJy beam}^{-1}$. The crosses indicate stellar velocities measured along the major axis by Simien & Prugniel (1997); they have been uniformly shifted in velocity by $12 \, \text{km s}^{-1}$ to make the systemic velocity of the stars agree with that of the molecular gas. The difference between heliocentric velocities (in the stellar data) and local standard of rest (in the CO) is $4 \, \text{km s}^{-1}$ at this position.
4.6. CO versus Stellar Morphology

Optical images from the red plates of the second-generation Digitized Sky Survey (DSS) were used in a comparison of CO and stellar morphologies. After sky subtraction, elliptical isophotes were fitted to the optical images. The ellipticity, position angle, and center of each isophote were allowed to vary freely. The isophote fits are generally not good within a semimajor axis of $5\,\alpha$, where the Sky Survey images are overexposed, or beyond $30\,\alpha$, where the images are underexposed. The region from $10\,\alpha$ to roughly $30\,\alpha$ is comparable to the size of the CO disks, and that is the region I focus on here. A second round of fitting, in which the ellipse centers were held fixed, did not significantly change the results over this radius range. For comparison purposes, elliptical isophote fits were also performed on the $J$, $H$, and $K$ images of NGC 4476 from the Two Micron All Sky Survey (2MASS) data. Isophote fits to NGC 3656 are more complicated because of the fine structure and the prominent dust lane, so the results of Balcells (1997) are used for that galaxy.

Table 6 gives the radius range over which the isophote fits are considered reliable, the mean ellipticity and position angle for each galaxy, and the dispersion about the mean for roughly 12 independently fitted annuli in that radius range. NGC 807, NGC 4476, and NGC 3656 are better described by $r^{1/4}$ surface brightness profiles than by exponential profiles over the radius range in question. UGC 1503 and NGC 5666 are about equally well fitted by either, although the reliable radius range for NGC 5666 is rather small. There is no evidence of position angle twist in any of the galaxies except for NGC 5666, which shows a $10^\circ$ change in position angle at semimajor axes around $15\,\alpha$. UGC 1503 shows no significant trend in ellipticity with radius, but the others do, and the dispersions about the mean ellipticities are determined mostly by the magnitude of those trends. The Sky Survey data for NGC 4476 give results that are consistent with those from the 2MASS data and the work of Prugniel, Nieto, & Simien (1987); my fits for UGC 1503 are consistent with those of Fasano & Bonoli (1989).

The stellar isophotes are significantly rounder than CO isophotes, as one would expect in the case where the stars are dynamically hot and gas is dynamically cold. The only exception to this statement is NGC 5666, where the stars and the gas have equal ellipticities within the errors. Table 6 also gives the misalignment angle between the optical major axis and the CO kinematic axis; except for NGC 3656,
which is close to a minor axis gas/dust disk, they are close to zero. In other words, four of the five galaxies have remarkably well aligned (within 13°) major axis gas disks.

5. DISCUSSION

5.1. The Origin of the Molecular Gas

Two ideas about the origin of molecular gas in ellipticals are (1) that the gas came from mass loss from the galaxy's own evolved stars or (2) that the gas was acquired in an interaction or a merger with another gas-rich galaxy. In the second category I also include the idea that the molecular gas in ellipticals may simply be left over from the formation of the elliptical, if ellipticals are formed by the merger of two roughly equal mass spiral galaxies (Toomre & Toomre 1972). In the first model, internal stellar mass loss, Faber & Gallagher (1976) estimate that mass-loss rates would be 1.5 $M_\odot$ yr$^{-1}$ per $10^{11} L_\odot$ of optical luminosity. Over 10$^{10}$ yr, this gas would be comparable to the observed gas masses, at
least within a factors of a few (the uncertainties in the H$_2$/CO conversion factor are at least factors of a few). The difficulty with this model is that the cold gas contents of elliptical galaxies are uncorrelated with their optical luminosities (Knapp, Turner, & Cuniffe 1985; Lees et al. 1991). Furthermore, the stellar mass loss is thought to be shock-heated by the stellar velocity dispersions to X-ray temperatures, and the hot plasma is thought to destroy dust grains on relatively short timescales (Wiklind & Henkel 2001).

The second idea, that the molecular gas in ellipticals has been acquired in a major or minor merger, may plausibly agree with the data presented here. Barnes (2002) has shown, via numerical simulations, that the merger of two gas-rich spiral galaxies produces systems that are qualitatively similar to the present sample of ellipticals and their gas disks. Some of the gas loses its angular momentum in shocks and falls to the nucleus of the galaxy, but up to 60% of the original gas contained in the spirals can form a rotationally supported gas disk with a radius of up to 20 kpc. Thus, the gas disks formed in these simulations are large enough to explain the observed gas disks (keeping in mind that the mass and size of the simulated disks are highly dependent on the geometry of the interaction). More careful analysis of the distribution and kinematics of the molecular gas in these ellipticals offers some important insight into these competing models and the origin of the molecular gas.

5.1.1. Gas and Stellar Kinematics

Figure 6e shows CO and stellar kinematics along the major axis of NGC 4476. The stellar kinematics are taken from Simien & Prugniel (1997), who also give a value of 14''/8 for the effective radius ($r_e$) of this galaxy. The CO velocity rises linearly with radius to a maximum velocity of 100 km s$^{-1}$ at 7'' radius. The stellar velocities also rise linearly with radius to a maximum rotation velocity of 35 km
s^{-1} (3 times smaller than the CO velocity) at 7'' radius. Beyond 7'', the stellar velocities appear to decline again, so that there is little sign of rotation at r_e.

The stellar velocity dispersion is \(65 \pm 13 \text{ km s}^{-1}\) in the center of the galaxy, much larger than the stellar rotation velocities; the stars are primarily pressure-supported rather than rotationally supported. This means that the stellar rotation velocities in Figure 6e significantly underestimate the circular rotation speed of the galaxy (the asymmetric drift effect). The cold molecular gas probably gives a good indication of the circular speed. But the stellar rotation velocities do indicate the specific angular momentum of the stars. Within r_e, the specific angular momentum of the gas is about 3 times larger than that of the stars. Furthermore, if the observed trend in stellar rotation continues beyond r_e, then the stars in the outer parts of the galaxy also have very small specific angular momentum. If internal stellar mass loss had produced this molecular gas, one would expect the gas to have the same specific angular momentum as the stars, or perhaps smaller, and this is clearly not the case. The only way to reconcile the specific angular momenta of the gas and the stars is to suppose that they have very different inclinations to the line of sight, but that would again be unlikely if the gas originated in the stars. An external origin for the gas in NGC 4476 is strongly favored.

A similar situation seems to be true for NGC 3656. Balcells & Stanford (1990) obtained stellar kinematics along two position angles, both of which are 50° away...
from the CO major axis. They infer that the maximum stellar rotation velocity in the inner 10″ is on the order of 50 km s\(^{-1}\) and that the stellar rotation axis is very close to what is now known to be the CO rotation axis. The CO rotation velocity is 270 km s\(^{-1}\), five times larger than that of the stars, but firm statements about the specific angular momenta of the stars and the gas are not possible in this case because the stellar rotation curve may still be rising at large radii. Similar comparisons of gas and stellar kinematics for the other galaxies in the sample will be vital for a broader understanding of the origin of the molecular gas in ellipticals.
5.1.2. Orientation of Molecular Gas and Dust

There are two cases in the present sample for which published optical images clearly show that there is a very close correspondence between the dust and molecular gas distributions. These cases include NGC 3656, mentioned in § 4.4, and NGC 4476. Tomita et al. (2000) show that the dust in NGC 4476 is settled into a very regular, highly inclined disk of diameter 20; the CO disk is also very regular, highly inclined, and has diameter of 27. The other galaxies of the present sample do not have good dust images in the literature, and dust features are not visible in the Digitized Sky Survey images, so detailed comparisons of their versus CO morphologies will require higher quality optical images.

As mentioned in § 5.1, the cold gas contents of ellipticals are unrelated to their optical luminosities, and this fact is usually interpreted as evidence of the gas’s external origin (Wardle & Knapp 1986; Lees et al. 1991). But the cold gas and dust distribution within an individual galaxy are clearly not independent of the stars. van Dokkum & Franx (1995) studied the orientations of dust features in Hubble Space Telescope (HST) images of ellipticals; they found that dust features with semimajor axes smaller than 250 pc are well aligned with the optical major axes of their host galaxies. More recent workers (Verdoes Kleijn et al. 1999; Martel et al. 2000; Tran et al. 2001) classify dust features into two classes: (1) smooth, regular disks and (2) irregular lanes or filaments. They find that the disks are closely aligned with their host galaxies’ major axes, whereas the lanes are randomly oriented. The interpretation common to all of these studies is that the dust has been acquired from an external source; the initial orientation of the dust features is random and their structure is irregular, but the dust gradually settles into the preferred plane of the galaxy and becomes a regular disk.

The close alignments between the CO disks and the optical major axes of the present sample are consistent with what is seen in the dust studies mentioned above, if the present sample of CO disks correspond to the older and more relaxed dust systems. Note, however, the curious fact that the CO disks studied here are larger than the dust features seen by van Dokkum & Franx (1995), Verdoes Kleijn et al. (1999), and Tomita et al. (2000). Most of the dust features have diameters smaller than 2 kpc, whereas only one of the CO disks (NGC 4476) is that small.

5.2. The Shape of These Galaxies

Many attempts have been made to infer the intrinsic shape distribution of elliptical galaxies from their optical photometry and kinematics, but the true shape distribution is still poorly known because it is model-dependent. Some ellipticals may be oblate, but it seems highly unlikely that all of them are (Kharurul Alam & Ryden 2002; Bak & Statler 2000 and references therein). However, the preponderance of major-axis disks in the present sample suggests that the majority of the sample galaxies are oblate. The principal plane of an oblate spheroid is perpendicular to the short axis, and this short axis always projects onto the apparent minor axis if the galaxy is axisymmetric (de Zeeuw & Franx 1989). Thus, a relaxed gas disk in an oblate galaxy should be aligned with the optical major axis.

At present it is not clear whether there is a discrepancy between the number of oblate ellipticals in the present sample and in the optical studies mentioned above. The number of elliptical galaxies with CO maps is still too small to confirm or reject the hypothesis that the CO sample has been drawn from the same parent population as the optical studies. But when the number of ellipticals with CO maps is significantly greater, it should prove interesting to investigate whether the amount of molecular gas in these galaxies correlates with their intrinsic shape.
5.3. Star Formation and the Future of the Molecular Gas

Molecular gas is understood to be the raw material for star formation; the transformation of gas into stars will create rotationally supported stellar disks within these ellipticals. An estimate of the masses of the stellar disks can be obtained from Table 5, which shows that the molecular gas masses in the sample galaxies are a few percent of the dynamical masses within the edge of the CO disks. Comparing the masses of the stellar disks to the masses of the spheroidal stellar components depends on an assumption that the dynamical mass within the CO disk arises mostly from stars. This assumption is reasonable for the galaxy interiors.2 It is also likely that not quite all of the gas will be transformed into stars. These assumptions imply that the stellar disks will have masses on the order of 1% of the total stellar mass in the galaxies — perhaps somewhat more, if some of the molecular gas has already been transformed into stars.

The stellar disks that are likely to form out of these molecular disks will be very similar to the stellar disks that are now known to be common at least in disky ellipticals. Scorza et al. (1998), Scorza & Bender (1995), Cinzano & van der Marel (1994), and others who have done detailed photometric and kinematic studies of ellipticals find that many ellipticals contain both the usual spheroidal component (a bulge) and a stellar disk. In this respect, the ellipticals have structure that is qualitatively similar to spirals, but with much larger bulge/disk ratios (Kormendy & Bender 1996). Scorza et al. (1998) and Scorza & Bender (1995) found that the stellar disks inside ellipticals are rotationally supported; their sizes vary widely but are commonly on the order of $r_e$, and their disk/bulge (luminosity) ratios are commonly a few percent, up to 0.3. Presumably, smaller stellar disks may exist as well but are more difficult to detect. In short, after star formation ceases and the molecular gas is gone, the current sample of ellipticals will look much like known disky ellipticals.

The formation of a rotationally supported stellar disk may already have happened in NGC 4476, where the stellar rotation appears to die out at the edge of the CO disk. I propose that careful kinematic analysis of that galaxy will show a small stellar disk of radius 15$''$ and circular rotation speed ~100 km s$^{-1}$ superposed on a largely nonrotating spheroidal population.

Interestingly, Naab & Burkert (2001) already predicted the existence of molecular gas disks in some ellipticals, at least in the scenario in which ellipticals are formed by the merger of two similar-mass disk galaxies. They found that purely collisionless mergers of disk galaxies do not reproduce the detailed kinematics of real elliptical galaxies (see also Bendo & Barnes 2000). In particular, the collisionless mergers do not have broad retrograde and steep prograde wings in the stellar line-of-sight velocity distributions, and those are the signatures of rotationally supported stellar disks. Therefore, Naab & Burkert (2001) suggested that real ellipticals with stellar disks must have first contained gas disks similar to the ones shown here; the gas disks later turned into stellar disks.

2 For NGC 4476, the effective radius of 14$''$ quoted by Simien & Prugniel (1997) is similar to the 13$''$ maximum radius of the CO (Table 4); the CO disk extends to approximately $r_e$. The other sample galaxies do not have published effective radii, but from Figures 3a, 4a, 5a, and 7a it seems unlikely that the CO extends to radii much larger than $r_e$.

5.4. Stability of the Asymmetries in NGC 807

The strong asymmetry in the CO distribution of NGC 807 ($\S$ 4.3) is striking, particularly in view of the fact that the gas should be sheared by differential rotation on very short timescales. Figure 4e shows that the rotation curve for NGC 807 becomes flat at a distance of 6$''$ (2.0 kpc) from the kinematic center of the galaxy. The peak of the CO distribution is about 9$''$ (2.8 kpc) from the center, well within the differentially rotating part of the galaxy. The orbital timescale at the farthest edge of the CO disk in NGC 807 is 1.5 $\times$ 10$^8$ yr (Table 5), and the orbital timescale at the turn-over point is only 5 $\times$ 10$^7$ yr. These numbers are not strongly dependent on the assumed inclination, since the sin$i$ correction is only 10% for the CO in NGC 807 (Table 5).

Thus, the effects of differential rotation should have been severe for this gas over the last 10$^8$ or few $\times$ 10$^8$ yr. It is difficult to understand how the strong asymmetry (twice as much emission from the southern half of the galaxy as from the northern half) could be maintained for as long as 10$^8$ yr. One possible solution to the problem is that the gas was acquired less than 10$^7$ yr ago. On the other hand, an interaction with another galaxy less than 10$^9$ yr ago should leave other traces as well — features like shells, ripples, or tails in the optical or H i images — but none have been seen (Oosterloo, Morganti, & Sadler 1999; Dressel 1987).

There are several other possible solutions to this short timescale for shearing. For example, the molecular gas may be much farther from the center than it appears. The orbital timescale would then be longer than 1.5 $\times$ 10$^8$ yr. This scenario implies a highly nonuniform distribution of molecular gas, which again might be evidence that the gas was acquired from some outside source. The molecular gas could be on elliptical orbits; the gas distribution should then show a peak in the place where the orbital speed is small. It is also possible that the peak in the CO intensity reflects not a peak in the total gas density but rather a change in the phase from atomic to molecular; comparisons with the atomic gas distribution could address this latter possibility.

One final way to avoid the shearing problem is if the molecular gas that peaks about 9$''$ south of the galaxy center (Figs. 4a and 4e) is strongly self-gravitating. This feature has a CO flux of 9.2 Jy km s$^{-1}$, so its mass (not including helium) is approximately 4.5 $\times$ 10$^8$ $M_\odot$. The mass and the fact that it is not well resolved in the spatial dimension are consistent with H$_2$ densities in the range 10$^2$–10$^3$ cm$^{-3}$ (4 $\times$ 10$^{-22}$ to 4 $\times$ 10$^{-21}$ g cm$^{-3}$, including helium), which are typical values for Galactic giant molecular clouds. From the rotation velocity of the CO we infer that the galaxy itself has a mass of 4.1 $\times$ 10$^{10}$ $M_\odot$ within 2.8 kpc of the center, giving an average density of 3.0 $\times$ 10$^{-21}$ g cm$^{-3}$. In these conditions the Roche limit for molecular gas of density 10$^2$–10$^3$ cm$^{-3}$ is 1.3–2.8 kpc, which implies that the molecular gas is quite close to the borderline between tidal instability and stability. Again, the molecular gas may be farther from the center than it appears, which would tend to increase its stability.

5.5. A Cautionary Note

Given that there are still only a very small number of ellipticals whose CO distribution has been mapped, it is important to remember that the CO distributions in the present sample may not be representative of ellipticals in
general. For example, the galaxies have been selected from single-dish surveys that usually only made one pointing toward the center of each galaxy. Any ellipticals in which molecular gas avoids the inner 10′′ (in radius) would not have been selected. Furthermore, the galaxies are selected to be bright at 100 μm, but it is well known that IRAS is much more sensitive to warm dust than to cold dust. Ellipticals whose dust is primarily cold would also not have been selected. If interactions increase the FIR luminosity of a galaxy, the present sample may be biased toward galaxies that have recently undergone an interaction. Future progress in understanding the evolution of ellipticals requires some exploration of these kinds of selection effects.

6. SUMMARY

Six elliptical galaxies from the CO survey of Wiklind, Combes, & Henkel (1995) and one from Sage & Wrobel (1989) were observed with the BIMA and OVRO millimeter arrays at about 8′′ × 6′′ resolution (0.7–2 kpc). Five of the seven (UGC 1503, NGC 807, NGC 3656, NGC 4476, and NGC 5666) were detected and their CO emission is resolved into very regular rotating disks. The disk radii are 1–6 kpc and rotation velocities are 100–280 km s⁻¹; orbital timescales at the edge of the disks are around 10⁸ yr.

Two of the five detected galaxies have CO rotation curves that rise linearly and then flatten at radii of 1–2 kpc. Two other galaxies’ rotation curves keep rising to the edge of the CO disk; one may flatten just at the outer edge of the CO. The sizes, observed velocities, and inclination angles of the disks enable robust dynamical mass estimates that range from 3 × 10⁹ M⊙ for NGC 4476 to 10¹¹ M⊙ for NGC 807. Of course, the dynamical mass estimates pertain to the mass interior to the edge of the CO disk, which for NGC 4476 is about one effective radius. The H₂ masses are only a few percent of the dynamical masses.

Four of the CO disks are aligned within 13° of their host galaxies’ optical major axes. The high proportion of major-axis gas disks suggests that these ellipticals are oblate. The exception, NGC 3656 (a merger remnant), has a gas and dust disk nearly aligned with its minor axis. The kinematics of the gas in NGC 3656 show clear evidence for a warp, but the others do not appear to be warped at the current resolution and sensitivity.

In one case, NGC 4476, major-axis stellar kinematics are available from the literature. The stars show some rotation over the radial range where the CO exists, but outside that range the stellar rotation velocity appears to drop to zero. The gas has a factor of 3 or so larger specific angular momentum than the stars, which strongly suggests that the gas in NGC 4476 has come from an external source rather than from internal stellar mass loss. However, the present analysis offers no insight into the question of whether the gas in NGC 4476 is leftover from a major merger or was acquired in a minor merger/interaction. The CO disks are well within the size range of the gas disks that are created in spiral-spiral merger simulations (Barnes 2002), so the major-merger hypothesis is plausible in this respect. Only one of the galaxies shows clear evidence of a major merger (NGC 3656; Balcells 1997; Balcells et al. 2001).

If the molecular gas in these galaxies forms stars, it will make rotationally supported stellar disks with radii of a few kpc. These stellar disks will probably contain on the order of 1% of the total stellar mass. The disks will be very similar in character to the stellar disks that are now known in many ellipticals (Scorza et al. 1998), although perhaps somewhat less luminous than the stellar disks that are detectable at present.

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