MOLECULAR GAS IN OPTICALLY SELECTED MERGERS

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Abstract

We have mapped the 2.6 mm CO $J = 1 \rightarrow 0$ emission in three optically selected “Toomre Sequence” mergers (NGC 520, NGC 3921, NGC 4676). The molecular gas distribution is well resolved by the observations. For NGC 520 and NGC 4676A, the nuclear gas concentrations form a disk- or a ring-like structure, and the gas kinematics are regular and are consistent with simple rotation. Discrete molecular gas complexes are found along the stellar bar in NGC 4676B, and the gas kinematics is consistent with the disk rotation traced in Hα. The molecular gas distribution in NGC 3921 is asymmetric about the stellar remnant, and both the distribution and kinematics suggest that the molecular gas has not settled into the center of the remnant. Molecular gas clouds are detected outside the central regions of NGC 3921 and NGC 4676, and they may be associated with the tidal tails and bridges mapped in H1. Departures from the canonical scenario for a merger involving two large spiral galaxies are found in all three Toomre Sequence mergers studied. Our data suggest that one of the progenitor disks in NGC 520 and NGC 3921 were relatively gas-poor. A detailed comparison of these optically selected mergers and more luminous IR selected mergers is deferred to a companion paper (Paper II).

Subject headings: galaxies: individual (NGC 520, NGC 3921, NGC 4676) — galaxies: interactions — galaxies: evolution — ISM: molecules

1. INTRODUCTION

It is widely believed that a physical collision between a pair of gas-rich galaxies leads to the concentration of gas and an intense starburst in the central region of the merger remnant (Toomre & Toomre 1972; Negroponte & White 1983). Indeed the majority of infrared bright galaxies are strongly disturbed systems, and massive concentrations of molecular gas have been detected in their central regions (see review by Sanders & Mirabel 1996 and references therein). However, this is not a complete and general picture of all galaxy collisions since many optically disturbed systems do not show strongly increased levels of massive star formation (Bushouse et al. 1988). The majority of recent studies have focused mainly on infrared (IR) selected galaxies, and information on the molecular gas content and distribution within merging systems of modest infrared luminosity is sparse in comparison.

A wide range of explanations are possible for the relatively modest levels of star forming activity observed in the optically selected colliding galaxies. Unlike the IR luminous systems, the progenitor disks of these systems may have been relatively gas-poor. Alternatively, the progenitors may have been gas-rich, but the initial conditions of the collisions were such that the bulk of the gas may have turned into stars or dispersed during the collision (e.g. Milos & Hernquist 1996). It is also possible that the IR luminous phase is generic but brief so that the less luminous mergers are seen in the pre- or post-burst phase in their evolution.

As a first step in investigating these possible scenarios, we have used Owens Valley Radio Observatory (OVRO) Millimeter Array to map the 2.6 mm CO $J = 1 \rightarrow 0$ transition line emission in three “Toomre Sequence” mergers: NGC 520, NGC 3921, and NGC 4676. The “Toomre Sequence” is an optically selected ensemble of strongly interacting galaxies representing a suggested evolutionary sequence of disk-disk mergers, based on their stellar tidal tail lengths and the separation of the two nuclei (Toomre 1977). Since the members of this sequence were selected on the basis of optical morphology alone, they are much less biased towards systems with very high star formation rates than IR selected samples.

The new high resolution interferometric CO observations allow us to map the distribution and kinematics of the molecular gas in order to investigate the response of the molecular material which was previously distributed in the inner disks of the progenitors. These data are compared with existing high resolution interferometric CO observations of IR luminous mergers in a separate paper (Yun & Hibbard 2000, hereafter Paper II). In particular, we address whether any systematic difference exists in the properties of the molecular gas (which directly fuels the starburst activity) between the less luminous mergers and the IR selected mergers that may explain the differences in the IR (and total) luminosity.

In §2 we describe the three Toomre Sequence mergers selected for this study. The details of the observations and data reduction are discussed in §3. The results are
The Toomre Sequence consists of “Eleven NGC Prospects for Ongoing Mergers”, as sketched and presented by Toomre (1977). The sequence was arranged based on the results of simple numerical simulations conducted by Toomre & Toomre (1972), which demonstrated the effects of bound gravitational interactions on the outer regions of disk galaxies. This seminal work illustrated that long filamentary features are the natural consequence of the tidal forces experienced during such encounters, at the rate of one tail per prograde disk. Although their numerical technique did not allow for the inclusion of orbital decay, Toomre & Toomre (1972) posited that such decay should occur, leading to the eventual merging of the participants. This proposal has been repeatedly confirmed with more sophisticated numerical treatments (see Barnes & Hernquist 1992, 1996; Barnes 1998 and references therein). The natural consequence of such encounters, the Toomres hypothesized, would be pairs of galaxies spiraling ever closer together, eventually leaving a single stellar body with two protruding tidal tails. The Toomre Sequence was meant to depict this proposed evolutionary sequence of disk-disk mergers.

Four members of the Toomre Sequence have previously been mapped in CO with the OVRO interferometer (NGC 4038/9 by Stanford et al. 1990; Wilson et al. 2000), NGC 520 by Sanders et al. 1988, NGC 2623 by Bryant & Scoville 1994, and NGC 7252 by Wang et al. 1992). These systems span the entire range of the sequence from beginning to end. We chose to improve our understanding of the dynamical effects occurring during merging encounters by observing additional systems at the beginning and end of the sequence (NGC 4676 and NGC 3921, respectively) and by re-observing NGC 520. We selected these three systems because there are VLA H I mapping and deep broad- and narrow-band optical observations available to help in the interpretation of the CO data (from Hibbard & van Gorkom 1996; hereafter HvG96). We chose to re-observe NGC 520 to target explicitly the second nucleus, which did not fall within the previously observed field (Sanders et al. 1988). Previous observations and a detailed description of the three systems are found in HvG96. Here we summarize their defining optical morphological features and their location along the Toomre Sequence. Excellent photographs of the systems can be found in the Arp “Atlas of Peculiar Galaxies” (1966), and CCD images of the entire systems, including the extended tidal features, are given in HvG96. In this paper we will restrict our figures to the inner few kpc of each merger, as this is where the CO is concentrated.

NGC 4676 (=“The Mice”=UGC 7938/9=Arp 242=VV 224) is the second member of the Toomre Sequence, representing an early stage merger where the two disks are separated by less than one optical diameter in projection but still distinct. A bright optical bridge connects the two disks, and two distinct bright optical tails, each about 50 kpc in projected length, are present.

NGC 520 (=UGC 966=Arp 157=VV231) falls near the middle of the Toomre sequence (7th of 11), representing an intermediate stage of merging where two distinct nuclei are seen embedded within a single stellar body. The primary nucleus is hidden beneath the prominent dust lane near the remnant body center, and the secondary nucleus is seen 40′′ (6 kpc) away towards the northwest. A bright optical tail stretches 25 kpc to the south, and a broad stellar plume is seen reaching 60 kpc to the northwest.

NGC 3921 (=UGC 6823=Arp 224=Mrk 430) is the next to last member of the Toomre Sequence. It represents the latest stages of a merger, with a single stellar remnant body exhibiting an r^{1/4} radial light profile, characteristic of normal ellipticals. The optical isophotes are not concentric (Schweizer 1996; hereafter S96), suggesting that the merger is not fully relaxed. A stellar tail stretches 65 kpc to the south, and a broad optical plume reaches 80 kpc to the northeast.

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The interpretation of the CO data (from Hibbard & van Gorkom 1996; hereafter HvG96). We chose to re-observe NGC 520 to target explicitly the second nucleus, which did not fall within the previously observed field. Previous observations and a detailed description of the three systems are found in HvG96. Here we summarize their defining optical morphological features and their location along the Toomre Sequence. Excellent photographs of the systems can be found in the Arp “Atlas of Peculiar Galaxies” (1966), and CCD images of the entire systems, including the extended tidal features, are given in HvG96. In this paper we will restrict our figures to the inner few kpc of each merger, as this is where the CO is concentrated.

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3. OBSERVATIONS

Aperture synthesis CO observations of NGC 520, NGC 3921, and NGC 4676 were carried out with the Owens Valley Millimeter Array between September 1994 and February 1995. There are six 10.4 m diameter telescopes in the array, providing a field of view of about 1' (FWHM) at 115 GHz. The telescopes are equipped with SIS receivers cooled to 4 K, and typical single sideband system temperatures were between 300 and 500 K. Baselines of 15-200 m E-W and 15-220 m N-S were used, and the details of the observations including the synthesized beams from naturally weighted data are summarized in Table 1. A digital correlator configured with 120 × 4 MHz channels (11.2 km s\(^{-1}\)) covered a total velocity range of 1340 km s\(^{-1}\). Nearby quasars (see Table 1) were observed at 25 minute intervals to track the phase and short term instrument gain. Uranus (\(T_B = 120\) K), Neptune (\(T_B = 115\) K), 3C 273, and 3C 454.3 were observed for the absolute flux calibration. The data were calibrated using the standard Owens Valley array program MMA (Scoville et al. 1992) and were mapped and analyzed using the imaging program DIFMAP (Shepherd et al. 1994) and the NRAO AIPS software system. The uncertainty in absolute flux calibration is about 15%, mainly due to the uncertainty in transferring the calibration between the sources and the flux calibrators.\(^3\) The positional accuracy of the resulting maps is better than \(\sim 0.5\)''.

A detailed study of all three systems has been conducted in the optical and 21 cm H\(_i\) emission by HvG96: radio synthesis observations of 21 cm H\(_i\) emission to obtain information on the distribution and kinematics of extended cold atomic gas; deep broadband \(R\) images to delineate the underlying stellar distribution and any faint optical tidal extensions; and narrow band H\(_\alpha\)+[N II] observations to reveal regions of current star formation. These data are compared to the CO distribution and kinematics in the present work, and are fully described in HvG96.

Additional optical and near infrared (NIR) data on NGC 3921 were needed in order to examine the dynamical state of this puzzling merger remnant. Broadband \(BVR\) observations of NGC 3921 were obtained in January of 1997 with the University of Hawaii 88'' (UH88'') telescope. The f/10 re-imaging optics were used with a Tek2048 CCD, resulting in a plate scale of 0.22'' pixel\(^{-1}\) and a field of view of 7.5''. The seeing was \(\sim 1''\), and total exposure times of (1200s, 900s, 600s) were obtained in \((B, V, R)\), respectively. The data were calibrated via observations of Landolt (1983, 1992) standards observed on the same nights, with resulting zero-point errors (1\(\sigma\)) of (0.01 mag, 0.02 mag, 0.03 mag) in \((B, V, R)\).

NIR observations were made at \(K'\)-band (\(\lambda = 2.15\mu m\), hereafter referred to simply as \(K\), Wainscoat & Cowie 1992), obtained with the QUIRC 1024 x 1024 detector.

\(^3\)Relative accuracy among the measurements presented here is significantly better, but the absolute uncertainty is offered because it is more relevant when comparing these measurements with other measurements.

Figure 1. CO (1–0) spectra of the Toomre Sequence mergers imaged. They are obtained by summing all detected fluxes in the individual channel maps (see Figures 3, 7, & 11). Single Dish spectra from the IRAM 30-m telescope (\(\theta_{FWHM}=22''\)) are shown in dotted lines (NGC 520 [Solomon et al. 1992], NGC 3921 [Combes, unpublished], NGC 4676 [Casoli et al. 1991]). The shape and the flux levels agree well between our measurements and the IRAM 30-m measurements, except in NGC 520 where the IRAM 30-m spectrum is significantly lower, possibly due to a pointing or calibration problem.
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on the UH88′′ telescope in January of 1995. The f/10 re-imaging optics were used, resulting in a plate scale of 0.187′′ pixel−1 and a field of view of 3′2. The observations consist of three 120 sec target-sky pairs, with the CCD dithered by 1.5′ between on-source positions. The NIR data are uncalibrated.

4. RESULTS

The observed and derived properties of the sample are summarized in Table 2 along with other properties of interest. The far-infrared luminosities4, \( L_{\text{FIR}} \), of these three merging systems range between \((1-5) \times 10^{10} L_\odot\), with a \( L_{\text{FIR}}/L_B \) ratio of unity for NGC 4676 and NGC 520 and about 0.2 for NGC 3921. Therefore these are modest starburst systems at best. The molecular gas masses5 detected in CO range between \((1-5) \times 10^9 M_\odot\), accounting for 40% to 100% of the gas masses inferred from single dish measurements. This is within a factor of two of the total molecular gas associated with our Galaxy \((3.5 \times 10^9 M_\odot); \text{Sanders et al. 1984}\). While the bulk of the molecular gas in our Galaxy is located within an annulus of 4-6 kpc radius, CO emission in these optically selected merger systems is concentrated to the central 2 kpc radius, except for NGC 4676B, whose total molecular gas content and distribution is not well determined by our data (see below).

The CO (1–0) spectra of each system are produced by summing the detected emission from each narrow band channel map and are shown in Figure 1. All of the CO (1–0) spectra show line widths and shapes comparable to the single dish spectra (shown in dotted lines; Casoli et al. 1991, Solomon et al. 1992, Combes personal communication). We do not recover the full line flux measured in the single dish observations in some cases (see Table 2). Since the interferometer lacks spacings shorter than about 10 meters, one possibility is that there is some extended CO emission (\( \theta > 45′′ \)) that is resolved out in our observations. Another possibility is that some of the line emission is lost to the limiting surface brightness sensitivity of the observations. The peak CO line brightness temperature observed is only about 0.3-0.6 K for NGC 3921 and NGC 4676 and 5.2 K for NGC 520. Since the intrinsic CO line brightness should be at least 10-20 K and may be as high as 30-50 K in starburst regions, the beam filling factor for the CO emitting regions must be quite small, less than 10% and significantly so in some cases.

The molecular gas distribution and kinematics in the individual systems are discussed in detail below. For all three observed mergers, we first compare the CO distribution with the R-band, narrow band Hα+[N II], and VLA H I distributions from HvG96. We then examine the full CO 3-dimensional kinematic information as traced by the individual channel maps. From these plots it is clear that

\begin{itemize}
    \item 4\( L_{\text{FIR}} \) represents the infrared luminosity in the 40–120 µm band, calculated from the 60µm and 100µm IRAS fluxes (see Helou et al. 1988).
    \item 5Standard Galactic conversion of \( N_{\text{H}_2}/I_{\text{CO}} = 3 \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1} \text{pc}^{-2})^{-1} \) is used (see Young & Scoville 1991).
\end{itemize}
the CO emitting molecular complexes are well resolved spatially and kinematically by the aperture synthesis observations presented here. We explore the CO kinematics by comparing the mean velocity and velocity dispersion maps. The mean velocity field gives an idea of the large scale orbital motions, and the intensity-weighted velocity dispersion helps identify the local centers of the gravitational potential or the sites of large peculiar velocities. Finally, we plot the kinematic profiles along the major axis, and compare these to the 21cm line data and any available optical kinematics.

4.1. NGC 4676

4.1.1. Molecular Gas Distribution

We mapped the CO (1–0) emission in NGC 4676 ($D = 88$ Mpc) at $2''8 \times 3''2$ (1.2 $\times$ 1.4 kpc) resolution. The array was pointed at the region between the two nuclei such that the primary beam (field-of-view) of the array includes the main bodies of both galaxies, but very little of the tidal tails (see Fig. 2a). Both NGC 4676A (north) and NGC 4676B (south) are detected in emission, and the integrated CO emission is contoured in Figure 2. About
Figure 4. (a) Velocity integrated CO (1–0) map of NGC 4676 in linear contours superposed over the Hα image. The contours are 10, 20, 30, 40, 50, 60, 70, 80, and 90% of the peak which is 18.4 Jy km s$^{-1}$ ($N_{H_2} \sim 6.1 \times 10^{22}$ cm$^{-2}$). Only weak CO emission is detected along the bar in NGC 4676B. The spatial correspondence between the CO and Hα is poor, and extinction by dust associated with the molecular gas ($A_V \sim 120$) offers a natural explanation in the edge-on system NGC 4676A. (b) Mean CO emission velocity plotted in contours (in km s$^{-1}$) superposed over the velocity dispersion ("second moment") map in greyscale. The linear greyscale range between 0 (white) to 160 km s$^{-1}$ (black). The velocity gradient is increasing to the north in both galaxies, and thus the spin orientation of the collision is in a prograde sense.

80% of the CO emission is associated with NGC 4676A while only weak CO emission is detected along the bar in NGC 4676B. The total detected CO flux in NGC 4676A is $54 \pm 8$ Jy km s$^{-1}$ (100% of the flux measured at the IRAM 30-m telescope by Casoli et al. 1991), which corresponds to a total molecular gas mass of $5.5 \times 10^9 M_\odot$ or about twice as much as in our Galaxy. In NGC 4676B we recover only 20% of the total single dish CO flux reported by Casoli et al. Our brightness sensitivity ($\Delta T_B = 0.08$ K) and a low beam filling factor may explain at least part of the “missing” flux. When the visibility data is tapered to $\sim 5''$ resolution, the recovered flux increased to $14 \pm 2$ Jy km s$^{-1}$, or about 40% of the total single dish flux. The CO morphology does not change substantially in the low resolution maps, however. The undetected single dish flux is associated with a distinct spiky spectral feature occurring between the velocity of 6400–6800 km s$^{-1}$ in Figure 1. This feature may arise from the molecular gas associated with the bridging region, poorly represented in our data due to a low beam filling factor. Alternatively, this feature may be CO emission from NGC 4676A picked up by the sidelobe response of IRAM 30-m telescope rather than being intrinsic to NGC 4676B.

The CO emission in NGC 4676A is clearly confined to a nearly edge-on disk-like structure with a deconvolved size of 1.8 kpc in radius and a thickness (FWHM) of 250 pc (see Table 2). A bridge of stars and gas connecting the two galaxies is clearly seen in the optical and H$\alpha$ emission (see Fig. 2c), and several CO clumps are also found in the bridging region (i.e. at velocities between 6516–6641 km s$^{-1}$ in Fig. 3) albeit with relatively low S/N. Only one such CO clump appears in the velocity integrated CO map (Figs. 2a & 4a), just southeast of the main body of NGC 4676A, because only the high signal-to-noise ratio ($\geq 5\sigma$) features are included in these maps. The presence of molecular gas in the bridging region suggests that the disruption of the inner disks ($R < 10$ kpc) has begun in NGC 4676. Most of the CO clumps seen in the channel map are unresolved ($\lesssim 1$ kpc in diameter) with molecular gas masses of $\sim 10^8 M_\odot$. They are somewhat larger and more massive than the giant molecular clouds (GMCs) in our Galaxy, and they may be responding ballistically to the tidal disruption. Alternatively, these CO clumps may be molecular gas condensations forming within the gaseous bridge traced in H$\alpha$ and may represent possible sites of future star formation.

One striking feature in the distribution of CO emission in NGC 4676 is the lack of any correspondence between the brighter H$\alpha$ peaks (presumably tracing the present sites of star formation) and the CO peaks (dense gas concentrations). Even a marginal anti-correlation is seen, particularly in Figure 4a which displays a wider intensity scale for the H$\alpha$ emission than shown in Fig. 2b. The brightest H$\alpha$ emission in NGC 4676A is located just outside the southern tip of the CO emitting region, and significant optical extinction in this nearly edge-on disk offers a natural
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Figure 5. Position-velocity plot of CO emission in NGC 4676A along the kinematic (and morphological) major axis is shown in greyscale. The molecular gas traces the kinematics of the inner disk with a rising rotation curve with a maximum rotation velocity of $270 \text{ km s}^{-1}$, which flattens at a radius of 960 pc. The contours represent the corresponding P-V plot of the 21 cm H I emission (from HvG), which is a good indicator of the extent of the outer disk with a flat rotation curve. They both suggest that the kinematics of the inner gas disk ($R < 4 \text{ kpc}$) is relatively undisturbed. The S-shaped morphology of the CO emission indicates that the molecular gas does not uniformly fill the disk outside 1 kpc radius and may be confined to a pair of tightly wound spiral arms.

explanation – the peak integrated CO flux of $18 \pm 3 \text{ Jy km s}^{-1} \text{ beam}^{-1}$ corresponds to $N_{H_2} = 6.1 \times 10^{22} \text{ cm}^{-2}$ and a mean visual extinction of $A_V \sim 120$ averaged over the $3''$ (1.3 kpc) beam. Even the lowest CO contour in Fig. 4a corresponds to $A_V \sim 12$.

For the more face-on galaxy NGC 4676B, CO and Hα emission do not correspond well either. The brightest Hα peak near the center of the galaxy has no associated CO emission. This may reflect the large extinction associated with the CO emitting clouds. Alternatively, this may indicate that the life time for young stars may be much longer than the cloud dispersion time scale. The observed “twin-peak” CO morphology is often seen in other barred galaxies, probably due to a bar-driven dynamical resonance within these disks [Kemey et al. 1992]. Figure 2b shows that both the CO and Hα bars are offset in the same manner from the underlying optical bar (HvG96). Similar offsets are seen in hydrodynamical simulations of mergers [Barnes & Hernquist 1991] and provide a means of transferring angular momentum from the gas to the stars, allowing the gas to settle even deeper into the potential.

Another notable aspect of the CO emission in NGC 4676 is the apparent contrast in CO luminosity and distribution between the two merging galaxies. We detect about 4 times more CO emission in NGC 4676A with a much more centrally concentrated distribution compared with NGC 4676B. The apparent contrast in the CO luminosity in the single dish measurements by Casoli et al. (1991) is about a factor of two, and some of the CO emission associated with NGC 4676B may extend beyond the inner disk region mapped by us (see above). One explanation for the apparent difference in the gas content is that the progenitor disk for NGC 4676B had less molecular gas. The two merging galaxies have similar total H I content (about $3 \times 10^9 M_\odot$ each; HvG96), but NGC 4676B appears to be an earlier Hubble type (SB0/a). In a survey of molecular gas content among S0 and Sa galaxies, Thronson et al. (1989) conclude that typical fractional gas masses in S0’s and Sa’s are about an order of magnitude less than those for Sb or Sc spirals, and Young & Knezek (1898) report the largest $M(H_2)/M(HI)$ ratios among the S0/Sa Hubble types. Alternatively, the two progenitor disks started off with similar amounts of molecular gas but evolved differently under the tidal disruption because of different internal structure or different spin-orbit alignment (see Mihos & Hernquist 1996). The difference between these two scenarios has important consequences for understanding how a gas disk responds to a tidal disruption. Our observations alone cannot distinguish the two however, and this issue needs to be addressed by future numerical studies.

6However, the scatter associated with the individual Hubble type is substantial in both studies.
4.1.2. Molecular Gas Kinematics

NGC 4676A shows a distinct and relatively intact molecular gas distribution with relatively undisturbed kinematics. The intensity weighted mean CO velocity is shown in contours superposed over the greyscale velocity dispersion (“second moment”) map in Fig. 4b. The velocity dispersion shown in Fig. 4b exhibit a distinct peak at the center of NGC 4676A. This arises from the rapid rise in the CO rotation curve, and therefore marks the dynamical center of this edge-on disk. The major axis position-velocity plot (Fig. 5) shows more clearly that the CO emitting molecular gas in NGC 4676A is in rotation about its center, and an apparent flattening of the rotation curve is hinted by the sudden drop in the velocity gradient outside the central 4''-5'' (2 kpc) region. The line-of-sight velocity for the CO emission sharply decreases at 275 (1.1 kpc) radius, forming an S-shaped feature in the position-velocity plot. As shown by the solid lines in Fig. 5, the H I rotation curve remains flat, and this CO kinematic signature probably does not indicate a real drop in rotation velocity and may arise from non-circular motions induced by a non-axisymmetric potential. A pair of tightly wound molecular spiral arms can also exhibit a similar kinematic signature.

The peak rotation velocities traced in CO, HI, and Hα are all about 270 km s$^{-1}$. The large aspect ratio of the CO emitting region suggests that the molecular gas disk is viewed within 5-10 degrees of being edge-on, and the observed peak rotation velocity should be a good estimate for the true disk rotation speed. The derived dynamical mass $M_{dyn} = \frac{V^2R}{G}$ inside the 1.8 kpc radius is then $2.9 \times 10^{10} M_\odot$, and the molecular gas mass inferred from the CO emission ($4.9 \times 10^8 M_\odot$) accounts for about 20% of this dynamical mass. This gas mass fraction is on the upper end of what is seen in ordinary disk galaxies (a few to 25%, see Young & Scoville 1991 and references therein).

The orbital motion of the molecular gas in NGC 4676B is more difficult to determine because of its more face-on projection and the patchy CO distribution. The observed CO kinematics is consistent with the Hα rotation curve derived by Milos et al. (1993) along the bar which shows a monotonic velocity gradient consistent with solid body rotation. Assuming a disk inclination of 45$^\circ$, the dynamical mass inside the 4 kpc radius is about $2 \times 10^{10} M_\odot$. The derived molecular gas mass fraction is then about 7%, which is more typical of undisturbed disk galaxies.

The systemic velocities of the two galaxies are very similar (NGC 4676A slightly more redshifted, by $\sim 60$ km s$^{-1}$), suggesting that the two disks are either near their orbital apocenter or moving mostly in the plane of the sky. The velocity gradient increases to the north in both galaxies, consistent with the H I kinematics reported by HV96 and the Hα kinematics measured by Stockton (1974) and Milos et al. (1993). The spin vector of the two disk are aligned with their orbital motion, and the large tidal tails emerging from both disks are naturally explained by this prograde spin-orbit resonance (Toomre & Toomre 1972). The CO emitting clouds seen in the bridging region between the two merging disks have the velocities intermediate between the systemic velocities of the two disks as expected.

$^7$The dynamical mass estimate depends on the assumed mass distribution, and a simple rotational support approximation may result in a slight over-estimation if the mass distribution is disk-like rather than halo-like (see Binney & Tremaine 1987).
4.2. NGC 520

4.2.1. Molecular Gas Distribution

We mapped the CO (1–0) emission in NGC 520 ($D = 30$ Mpc) at $2''3 \times 2''7$ ($0.34 \times 0.41$ kpc) resolution, which is a factor of two improvement over the previous OVRO CO map by Sanders et al. (1988; $6'' \times 5''$). Two separate fields were observed, one centered on each of the near-infrared nuclei (Stanford & Balcells 1990), but CO emission is detected only around the main nucleus (see Fig. 6a). The $3\sigma$ upper limit for the molecular gas mass within the 1.3 kpc diameter region surrounding the second nucleus is $5 \times 10^6 M_\odot$ assuming a total line width of 60 km s$^{-1}$. This is less than 0.3% of the molecular gas mass associated with the main nucleus, and the contrast in the associated gas mass is quite dramatic. The absence of an associated molecular gas complex is somewhat unusual if this were a true stellar nucleus of a late type galaxy, and we will discuss this point further below (see §5).

Nearly all of the $3.0 \times 10^9 M_\odot$ of molecular gas detected in the main nucleus position is concentrated in the $1.0 \times 0.4$ kpc (PA=95$^\circ$) disk mapped by Sanders et al. (1988), coincident with the bright, extended nuclear radio source (Condon et al. 1990). The mean $H_2$ density is about $10^3$ cm$^{-3}$ if the molecular gas is uniformly distributed in a disk with 500 pc radius and 100 pc thickness, as if the entire molecular complex is a single super-massive giant molecular cloud. The full resolution data results in a detected flux of $285 \pm 43$ Jy km s$^{-1}$, which is less than the 325 Jy km s$^{-1}$ detected by Sanders et al. (1988). Smoothing the data to the $6''$ resolution of the Sanders et al. recovers a total flux of $404 \pm 61$ Jy km s$^{-1}$. The lower resolution maps do not reveal any additional features in the CO maps. Our measured flux corresponding to 58% of the total CO flux measured by the 14-m FCRAO telescope in its central 45$''$ beam area (Young et al. 1995). Solomon et al. (1992) report a total integrated line flux of only 211 Jy km s$^{-1}$ within the 22$''$ beam of the IRAM 30-m telescope. Therefore it is likely that we recovered most of the flux associated with the nuclear molecular disk, but there may also be significant systematic errors associated with all of these line flux measurements compared.

The partial mapping of CO emission by Young et al. suggests that CO emission extends beyond the nuclear region, along the stellar body of the galaxy (PA~45$^\circ$). This extended CO emission is not detected, either because it is

![Figure 7](image-url)
resolved out by the interferometer or because it has insufficient filling factor to be detected by the brightness limit of the synthesized beam ($\Delta T_B = 0.18$ K). Evidence for some extended, diffuse gas is seen in the channel maps (Figure 7, especially channels at 2195 km s$^{-1}$ and 2153 km s$^{-1}$), and its position angle with respect to the nuclear disk suggests that the extended gas may be associated with either the large scale H i disk or with the gas entrained in a galactic superwind emerging along the minor axis (HvG96).

The anti-correlation between H$\alpha$ and CO emission is even more dramatic in the nuclear region of NGC 520. The clear displacement of the CO emission from the H$\alpha$ distribution shown in Figure 8a suggests that the H$\alpha$ emission associated with the nuclear starburst is completely obscured by the dust within the nuclear gas disk. The peak integrated CO flux of 63.9 Jy km s$^{-1}$ corresponds to a mean column density of $N_{H_2} = 3.0 \times 10^{23}$ cm$^{-2}$ averaged over the 2f$^2$ (375 pc) beam, and the inferred large optical extinction ($A_V \sim 600$) is entirely consistent with the complete obscuration of the nuclear starburst by the CO emitting clouds. The observed H$\alpha$ emission is likely dominated by the starburst driven ionized wind escaping along the poles and some scattered light from the nuclear starburst region. The 1.4 GHz radio continuum map of the nucleus of NGC 520 by Condon et al. (1990) is essentially identical in appearance and dimension ($5'' \times 2''$ PA =93$''$) and is coincident with the CO disk shown in Fig. 8a. This is further strong evidence that the vigorous starburst activity is indeed associated with the molecular gas complex but entirely obscured. Similarly heavy obscuration of the starburst is found in other well studied nuclear starburst systems such as Arp 220 (Scoville et al. 1997). The observed anti-correlation between CO and H$\alpha$ not only confirms the diminished H$\alpha$ emission from massive young stars by extinction (e.g. Bushouse et al. 1988, Kennicutt 1989, Cram et al. 1998), but it also casts a serious doubt on star formation rates inferred from optical or UV tracers for such starburst systems.

The appearance of the brightest CO emission at the most extreme velocities seen in the major axis position-velocity plot (Figure 9) as well as the flatness of the CO emission along the major axis in the velocity integrated map (Fig. 8a) suggests that the CO emission does not rise monotonically inwards but has a central hole, i.e. there is a nuclear molecular torus rather than a disk (contrast CO contours in Fig 8a with those for NGC 4676A in Fig. 4a). This geometry has some similarity to the molecular torus found in the nuclear starburst region in M82 (Lo et al. 1987, Shen & Lo 1995), and such a central hole may be a common feature among nuclear starburst systems (e.g. Downes & Solomon 1998, Carilli et al. 1998).

4.2.2. Molecular Gas Kinematics

The intensity weighted mean CO velocity is shown in contours superposed over the greyscale velocity dispersion map in Fig. 8b. The CO emitting molecular gas in the nuclear region of NGC 520 shows a smooth, monotonic velocity gradient of 0.36 km s$^{-1}$pc$^{-1}$, which is a clear signature of rotation about its center. The regular interval of the iso-velocity contours suggests a solid body...
Figure 9. Position-velocity plot of CO emission in NGC 520 along the kinematic (and morphological) major axis is shown in greyscale. The constant linear gradient suggests that the molecular disk in NGC 520 lies within the solid rotation part of the inner disk. The dark contours represent the corresponding P-V plot of 21cm \(\text{HI}\) emission (dotted lines represent \(\text{HI}\) absorption – from HvG96), and the comparison with the CO emission suggest that the rotation curve turns over at the location of the outer radius of the molecular disk at a 500 pc radius with a maximum rotation speed of 200 km s\(^{-1}\). The brightest CO emission occurs at both extreme velocities, suggesting that the CO emission decreases towards the center (see §4.2.2).

rotation, which is more evident in the major axis position-velocity plot shown in Fig. 9. The 21cm \(\text{HI}\) absorption (dotted contours) coincides with that of the CO emission, and this suggests the presence of neutral atomic gas intermixed with the molecular gas in the nuclear starburst region.

The CO line widths are represented by the greyscale image in Fig. 8b. The broadening of the line width towards the center of the CO complex suggests that the molecular gas is well centered on the galaxy nuclear potential. The channel maps and the iso-velocity contours suggest that the molecular gas disk (or torus) is well resolved and is close to but not exactly edge-on. Assuming an intrinsic thickness of 100 pc, we infer an inclination of 70° to 75° from the aspect ratio of the CO emitting region. The peak rotation velocity traced in CO is about 200 km s\(^{-1}\) (210 km s\(^{-1}\) correcting for \(i = 70°\)). Then the dynamical mass inside 500 pc radius is \(4.9 \times 10^9 \, M_\odot\), and the \(\text{H}_2\) mass inferred from the CO emission \(\left(4.3 \times 10^9 \, M_\odot\right)\), nearly entirely accounts for the total mass inside the 500 pc radius region. This is a larger fraction than in NGC 4676A (§1.1.2) and is similarly dominant as in the IR luminous mergers such as Mrk 231 and Arp 220 (Bryant & Scoville 1996, Scoville et al. 1997). The higher density and temperature conditions associated with the intense starburst regions may result in an over-estimation of molecular gas mass if the standard CO-to-\(\text{H}_2\) conversion is used (Scoville et al. 1997, Downes & Solomon 1998), and the actual molecular gas mass traced by CO emission may be smaller by a factor of two or more. The orbital period at 500 pc radius is \(2 \times 10^7\) years, which is comparable to the time scale for the starburst but two orders of magnitude smaller than the dynamical time scale for the merger (HvG96).

One unusual aspect of the nuclear gas torus is that its position angle and angular momentum vector are misaligned with the larger scale stellar structures and outer \(\text{H}_1\) disk. A similar misalignment of the nuclear disk is seen in other nuclear starburst systems like M82 and may be produced by accretion of inflowing gas with misaligned angular momentum. The observed behavior is probably transient in nature as the continuing infall of mass and resulting torque will continue to shape the potential. The systemic velocity of the molecular gas disk, 2247 km s\(^{-1}\), is in good agreement with that of the large scale stellar and \(\text{H}_1\) disks (Stockton & Bertola 1980, Stanford & Balcells 1990, HvG96).

4.3. NGC 3921

4.3.1. Molecular Gas Distribution

NGC 3921 \((D = 78\) Mpc) was detected previously in CO \((1-0)\) and CO \((2-1)\) emission with the IRAM 30 m telescope by Combes and collaborators (Combes, personal communication). We mapped the CO \((1-0)\) emission in NGC 3921 at \(2''\times 2''\) \((0.87 \times 1.0 \, \text{kpc})\) resolution, finding the emission confined to at least two separate complexes (Figure 10): a main complex of 2 kpc diameter near the center of the field, and an unresolved CO emitting cloud
located 7\arcsec (2.6 kpc) south of the nucleus. The inferred molecular gas masses are 1.6 \times 10^9 \, M_\odot and 2.0 \times 10^8 \, M_\odot, respectively. We recover all of the CO flux detected at the central position by the 22\arcsec beam of the IRAM 30 m telescope (see Fig. 1 & Table 2), but the CO emission may extend beyond the area we mapped (Combes, personal communication). The mean H$_2$ density for the main molecular gas complex is $\sim$ 150 cm$^{-3}$ if the assumed line of sight thickness is 100 pc. This mean density is about 1/6 of that in NGC 520 but comparable to the typical density in Galactic GMC’s.

The integrated CO emission map and the derived mean velocity field are shown in comparison to the HI and Hα emission in Figures 10 & 12. The locations of the optical, near-infrared, and radio continuum peak are coincident to within a fraction of an arcsecond, and the mean position is marked with a cross. The main molecular complex in NGC 3921, however, is displaced by about 2\arcsec ($\sim$ 760 pc) to the west from this location. This suggests that either the gas is physically displaced from the optical nucleus, or that the true nucleus lies totally obscured beneath the CO complex (as is the case for NGC 520 and NGC 4676A).

These possibilities are further investigated by comparing the CO distribution with the optical and NIR (2.15\mu m) images, as shown in Figure 13. The optical and NIR images are found to be coincident to within a fraction of a pixel ($\sim$ 0.2\arcsec), while the peak of the CO emission is displaced by at least 10 pixels (2\arcsec) to the west. Further, the $K$-band image and $B - K$ color map shows no hint of a hidden NIR peak beneath the CO complex. While the peak extinction inferred from our CO observation is large ($A_V \sim 70$, $A_K \sim 7$), evidence for a second nucleus would be visible in the NIR image if an extended stellar bulge is present. It therefore seems that the observed displacement between the molecular gas and the stellar nucleus is real. The CO emission appears to be associated with a concentration of dust, as indicated by the dark greyscales in the $B - K$ map in Fig. 13.

A comparison between the gas distribution and the HST Planetary Camera (PC) image of NGC 3921 by Schweizer et al. (1996; see especially their Figure 4) supports this picture. This comparison is shown in Fig. 14, where the CO emission is contoured upon the $V$-band PC image of NGC 3921 of Schweizer et al. and upon the same image after a best-fit model light distribution has been subtracted. In the latter image dust lanes show up in white, and we confirm the conclusion reached above that the main CO complex coincides with an intricate system of dust lanes concentrated mainly to the west of the nucleus. Such a displacement is unexpected since the highly dissipative nature of the cold gas should cause it to settle into the gravitational potential within an inner dynamical time of $\sim$ 10$^7$ years. The non-axisymmetric appearance of the dust lanes gives the impression that the gas continues to spiral in towards the center, and the gas may be still settling within the merger potential. The combination of off-centered or “sloshing” optical isophotes and non-axisymmetric dust lanes and disordered kinematics led Schweizer et al. (1996) to suggest that “on scales of order 100–1000 pc the gas and dust in NGC 3921 do not form a well settled nuclear disk”. The displaced CO appears to be a strong confirmation of this interpretation.

The molecular gas clump located to the south of the main complex lies along the ridge of optical, Hα, and H I
molecular gas kinematics

The CO channel maps for NGC 3921 are given in Fig. 11. These maps show a general southwest-to-northeast velocity gradient along the main CO complex. However, numerous peaks and extensions appear and disappear in different channels at various position angles. The southwest complex appears at velocities between 5752–5838 km s\(^{-1}\), but with a velocity gradient opposite in sense to the main complex (i.e., decreasing velocities from south to north). The intensity weighted mean CO velocity, shown as contours superposed over a greyscale of the velocity dispersion map in Fig. 12b, also show the same gradient along the main CO complex and the velocity reversal in the SW complex. On the other hand, the local maximum in velocity dispersion characteristic of a local gravitational potential well is not seen in Fig. 12b, supporting the conclusion reached earlier that no distinct potential maximum exists within the main molecular gas complex.

Towards the main body, the H\(_i\) column density drops rapidly, and the H\(_i\) tail cannot be traced as an individual kinematic structure. The H\(_i\) which appears projected onto the main body is spread over a broad range of velocities, similar in width to the OVRO and single dish profiles.

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The position-velocity plot of the CO data is not very informative, so we instead illustrate the CO kinematics by comparing them to the optical emission line kinematics of S96, which were taken through a 2′ slit centered on the optical nucleus at a PA of 45°. This comparison is presented in Figure 15. The emission line kinematics are in general agreement with that the CO, suggesting that the two are tracing the same feature. To the SW, both the optical emission lines and CO show a sudden velocity reversal to lower velocities, showing that neither component clearly traces a simple rotation about the central potential. S96 derives a systemic velocity of 5926 km s\(^{-1}\) for NGC 3921, which was taken through a 2′ slit centered on the optical nucleus at a PA of 45°. This comparison is presented in Figure 15. The emission line kinematics are in general agreement with that the CO, suggesting that the two are tracing the same feature. To the SW, both the optical emission lines and CO show a sudden velocity reversal to lower velocities, showing that neither component clearly traces a simple rotation about the central potential. S96 derives a systemic velocity of 5926 km s\(^{-1}\) from the emission lines, while the CO data may suggest a somewhat lower value. However, given the lack of a recognizable systematic rotational signature, we believe the data are inconclusive as to this point.

The observed velocity reversals are very similar to those seen in the well studied merger remnant NGC 7252. A comparison between the Hα (Schweizer 1982) and CO (Wang et al. 1992), and tidal H\(\text{I}\) kinematics in that system (Hibbard et al. 1994) show that the velocity reversals occur where tidal features are projected near the inner regions, and can be explained by supposing that strong streaming motions of infalling gas from the tidal regions are superposed upon the kinematics of a central molecular disk. In NGC 3921 the velocities of the southern clump (encircled “S” in Fig. 15) appear at similar velocities as the blueshifted ionized gas. These velocities are also similar to the H\(\text{I}\) velocities at the base of the southern tail (HvG96), and this kinematic component may be associated with infalling gas from the tidal regions.

In summary, the inner region of NGC 3921 has an off-center molecular gas complex which has not settled into a disk, and a second component of gas may be infalling from the tidal regions. This is rather different from the nuclear molecular complexes seen in most single nucleus mergers, a point we will return to below.

### 5. Discussion

The majority of mergers mapped in CO show a central molecular disk with well defined rotational kinematics (Scoville et al. 1997, Downes & Solomon 1998, Bryant & Scoville 1999). Early gas inflow and the formation of a compact nuclear gas complex, even before the coalescence of the two stellar nuclei, are also seen in numerical studies of galaxy merger (e.g. Barnes & Hernquist 1996). This is a direct consequence of the fact that gas can shock and radiate energy away.

While some of the observed properties of these three Toomre Sequence mergers follow this canonical picture of a merger involving two large spiral galaxies, significant departures are also found. A dense concentration of molecular gas is associated with the central nucleus of the late stage merger NGC 520, but no other molecular gas concentration is detected on the second nucleus or along the region bridging the two nuclei. The formation of a compact nuclear gas complex appears to be well underway in the merging disk of NGC 4676A, but evidence for gas in-
Figure 13. Comparisons of integrated CO emission in NGC 3921 with $B$, $K$, and $B-K$ images. A cross in each image marks the center of NGC 3921 as determined from the HST observations of Schweizer et al. (1996). The spatial offset of the central CO complex from the stellar nucleus is apparent in all continuum band images. Absence of any K-band emission coincident with the CO feature rules out the possibility of an obscured nucleus within the molecular gas complex. A spatial correspondence is found between the CO emission and the dust lanes to the northwest (darker $B-K$ colors in the lower panels). The CO is contoured at 10, 20, ..., 90% of its peak value. North is up and East to the left, with vertical tic-marks drawn every 1$''$ and horizontal tic-marks drawn every 0.1 sec.

flow and formation of a central gas concentration is not evident in NGC 4676B. In NGC 3921, the molecular gas complex is significantly displaced from the peak of the optical, near-infrared, and radio continuum emission ($\sim 760$ pc).

One possible explanation for these departures from the canonical merger scenario is that one or both progenitor disks of these optically selected merger systems may have been relatively gas-poor. Based on the analysis of the stellar and H I tidal features, Hibbard & van Gorkom (1996) suggest that both NGC 520 and NGC 3921 are the products of an encounter between one gas-rich disk and one gas-poor system, such as an S0 or Sa galaxy (e.g. Thronson et al. 1989).

This suggestion for NGC 3921 is further supported by the observations of Schweizer et al. (1996), who find many fewer young globular clusters in this system compared to the gas rich mergers NGC 4038/9 and NGC 7252. The absence of molecular gas directly associated with the second nucleus of NGC 520 and the stellar nucleus of NGC 3921 is then naturally explained if little molecular gas has been funneled into the nuclei during the merger process. The absence of gas in one progenitor also lessens the frequency of gas cloud collisions in the second disk, especially within the central few kpc (Ollon & Kwan 1990), and therefore less dissipation and angular momentum transport is expected.

The presence of two large, atomic gas-rich tidal tails associated with NGC 4676 suggests that both progenitor disks were gas-rich (see HvG96), and a different explanation may be needed. As stated earlier, NGC 4676B appears to be an early Hubble type spiral and may also have been relatively molecular gas poor initially. A numerical study by Mihos & Hernquist (1996) has shown that the presence or absence of a massive bulge in the progenitor disk can produce a large difference in the evolution of the gas distribution and kinematics, the peak gas density achieved, and the resulting star formation activity. The apparent difference between the current molecular gas content in the two merging disks in NGC 4676 may
be explained more naturally by differences in the internal structure of the progenitors.

While it is significant that these three optically selected mergers show notable departures from the canonical merger scenario, we should also keep in mind that they nevertheless represent only three individual snapshots of their respective merger evolutions. For example, the apparent difference in the status of molecular gas between the two merging disks in NGC 4676 may simply reflect a slight delay in the onset of the gas inflow created by the difference in the spin-orbit coupling, however fortuitous this may seem. Similarly, NGC 3921 may be in a brief, early stage in its merger evolution and may soon develop a molecular disk. Schweizer (1996) has also presented observation evidence that NGC 3921 is a dynamically young merger. However, central CO disks are commonly found in both earlier (e.g. NGC 520 and NGC 4676A) and later stage (e.g. NGC 7252) mergers. One may further postulate that NGC 3921 represents a stage even further in its evolution where the original central gas complex is already dispersed. In this scenario, the observed gas in the central region is largely the result of recent inflow from the tidal tails (see Hibbard & Mihos 1995).

Finally, a clear and significant quantitative result from this imaging study of optically selected merger systems is that their central molecular gas surface density is systematically smaller by orders of magnitude compared with the IR selected mergers (see Table 2). Further, the level of activity associated with each of the merger systems appears to depend strongly on the central gas density. We will discuss this and other comparisons of global properties between the optically selected and IR selected mergers in a separate paper (Paper II).

6. SUMMARY

In an effort to better understand the nature of the luminous infrared galaxy phenomenon and to scrutinize the details of the merger scenario, we have mapped the CO emission in an optically selected sample of on-going mergers with moderate IR luminosity ("Toomre sequence", Toomre 1977) at a resolution and sensitivity comparable to those of the more IR luminous objects, and the response of the molecular gas material deep inside the potential of the colliding galaxies is traced. The summary of our findings is as follows:

1. A compact ($R \leq 2$ kpc) molecular complex is found well centered on the inner stellar disk of NGC 4676A, forming a disk- or a ring-like structure with the regular kinematics consistent with simple rotation. This molecular gas concentration contributes a significant fraction (20%) of the total mass in the nuclear region. The CO emission occurs along the 7 kpc stellar bar in NGC 4676B. The surface brightness of the CO emission is extremely low, and tapering the data from $3''$ to $5''$ resolution nearly doubles the detected flux.

2. Nearly all of the CO emission detected at the primary nucleus position in NGC 520 is concentrated in a 1 kpc diameter ring-like structure, coincident with the extended radio continuum source mapped by Condon et al. (1990). The derived H$_2$ mass and the dynamical mass are comparable, and the gas mass must constitute a large fraction of the total mass in the nuclear starburst region. No CO emission is detected on the second nucleus in NGC 520.

3. The molecular gas distribution in NGC 3921 is quite different from any other singly nucleated merger mapped in CO. The CO emission is significantly displaced from the
peak of the optical, near-infrared, and radio continuum emission (~760 pc), and both the distribution and kinematics suggest that the molecular gas has not settled into the new remnant potential. The molecular gas complex contributes a minor fraction (≤10%) of the dynamical mass in the inner regions.

4. Molecular gas clouds are detected outside the central regions of NGC 3921 and NGC 4676. They may be associated with the tidal tails and bridges mapped in H I.

5. A consistent trend of anti-correlation is seen between CO and Hα emission in NGC 520 and NGC 4676A, and the large extinction inferred from the CO emission (AV = 600 & 120) suggests that the intense nuclear starburst regions in these galaxies are completely obscured. This finding offers a natural explanation for the severe under-estimation of the star formation rate by optical tracers compared with the IR (e.g., Bushouse et al. 1988, Kennicutt 1989, 1998).

6. Departures from the canonical scenario for a merger involving two large spiral galaxies are found in all three Toomre Sequence mergers studied. A relatively gas-poor progenitor, as inferred from the optical and H I observations by HvG96, offers a possible explanation for NGC 520 and NGC 3921. A gas-poor progenitor disk or rapid evolution in gas content by some dynamical process (i.e., Mihos & Hernquist 1996) may offer a plausible explanation for the low molecular gas density in NGC 4676B.

7. The central molecular gas density in these optically selected mergers is systematically smaller by an order of magnitude compared with the IR selected mergers, the level of activity associated with each of the merger systems appears to depend strongly on the central gas density. This and other detailed comparisons of global properties between the optically and IR selected mergers will be presented in Paper II.

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resolved by IRAS, and the FIR fluxes are estimated by the ratio of their 1.4 GHz radio continuum flux ratio. 

$S_{1.4}$GHZ (mJy)$^b$

| RA (1950) | NGC 4676A | NGC 4676B | NGC 520 | NGC 3921 |
|-----------|-----------|-----------|---------|---------|
| 12:43:14.1 | 12:43:45.3 | 01:21:59.6 | 11:48:28.9 |
| Distance (Mpc)$^a$ | 88 | 88 | 30 | 78 |
| $< V_{CO, hel} > \text{(km s}^{-1}\text{)}$ | 6632±42 | 6590±42 | 2247±21 | 5880±42 |
| $\Delta V_{CO, FWHM} \text{(km s}^{-1}\text{)}$ | 546±42 | 252±42 | 499±21 | 462±42 |
| Deconvol. Size (PA) | 30°×1′ (5′) | 16°×2′ (22′) | 7′×2′ (95′) | 5′×2′ (38′) |
| $\Delta N_{CO, peak}$ | 0.60±0.09 K | 0.28±0.04 K | 5.2±0.7 K | 0.64±0.09 K |
| $S_{CO}\Delta V \text{(Jy km s}^{-1}\text{)}$ | 54±8 | 14±2 | 404±61 | 25±4 |
| Single Dish$^b$ | 55 | 34 | 696 | 21 |
| $M_{H_2, OVRO} \text{(M}_\odot\text{)}$ | (4.9±0.7)×10$^5$ | (1.3±0.2)×10$^5$ | (4.3±0.7)×10$^5$ | (1.8±0.3)×10$^5$ |
| $N_{H_2, peak} \text{(cm}^{-2}\text{)}$ | (6.1±0.9)×10$^{22}$ | (1.6±0.2)×10$^{22}$ | (3.0±0.5)×10$^{23}$ | (3.7±0.6)×10$^{22}$ |
| $\Sigma_{H_2} \text{(M}_\odot \text{pc}^{-2})$ | 900±135 | 210±32 | 4670±700 | 540±270 |
| mean | 340±51 | 24±4 | 2650±400 | 134±20 |
| $S_{1.4} \text{GHZ (mJy)}$ | 23.6 | 6.6 | 158 | 9.4 |
| log $L_{1.4} \text{GHZ (W Hz}^{-1}\text{)}$ | 22.0 | 21.4 | 21.9 | 21.5 |

$^a H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ assumed.

$^b$ Single Dish references: NGC 4676: Casoli et al. (1991); NGC 520: Young et al. (1995); NGC 3921: Combes, personal communication.

$^c$ $M_{H_2} = 1.2\times10^4 S_{CO} \Delta V D_{dpc}^2 M_\odot$ (see Sanders et al. 1991).

$^d$ $\Sigma_{H_2} = M_{H_2} \times \left[\frac{10^{-22}}{\text{cm}^{-2}}\right]^{-1}$

$^e$ From HvG96.

$^f$ From IRAS ADDSCAN/SCANPI (see Helou et al. 1988).

$^g$ $L_{FIR} = 4\times10^9 (2.58 S_{60\mu} + S_{100\mu}) D_{dpc}^2 L_\odot$ and assuming dust emissivity $n = 1$ (see Helou et al. 1988). NGC 4676 A&B are not resolved by IRAS, and the FIR fluxes are estimated by the ratio of their 1.4 GHz radio continuum flux ratio.
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