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Atomic and Molecular Gas in Colliding Galaxy Systems: I. The Data

Daisuke Iono[1,2], Min S. Yun[1], Paul T. P. Ho[2]

ABSTRACT

We present H I and CO (1–0) interferometric observations of 10 comparable-mass interacting systems obtained at the Very Large Array (VLA) and the Owens Valley Radio Observatory (OVRO) millimeter array. The primary intent of this study is to investigate the response of cold gas during the early stages of collision of massive disk galaxies. The sample sources are selected based on their luminosity ($M_B \leq -19$), projected separation (5-40 kpc), and single dish CO (1–0) content ($S_{CO} \geq 20$ Jy km s^{-1}). These selection criteria result in a sample that primarily consists of systems in the early stages of an interaction or a merger. Despite this sample selection, 50% of the systems show long H I tidal tails indicative of a tidal disruption in a prograde orbit. In addition, all (4/4) of the infrared luminous pairs (LIRGs) in the sample show long H I tails, suggesting that the presence of a long H I tail can be a possible signature of enhanced star formation activity in a collision of gas-rich galaxies. More than half of the groups show a displacement of H I peaks from the stellar disks. The CO (1–0) distribution is generally clumpy and widely distributed, unlike in most IR-selected late stage mergers – in fact, CO peaks are displaced from the stellar nucleus in 20% (4/18) of the galaxies with robust CO detection. H I and CO (1–0) Position Velocity Diagrams (PVDs) and rotation curves are also presented, and their comparison with the numerical simulation analyzed in Paper I show evidence for radial inflow and wide occurrences of nuclear molecular rings. These results are further quantified by examining physical and structural parameters derived in comparison with isolated systems in the BIMA SONG sample in our forthcoming paper.

Subject headings: galaxies: interactions,galaxies: evolution,galaxies:ism, galaxies: kinematics and dynamic, galaxies: individual (NGC 5257/58, NGC 5394/95, UGC 12914/15, NGC 5331, NGC 6621/22, UGC 813/6, NGC 7253/54, NGC 4567/68, NGC 7592, NGC 5953/54)

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1. Introduction

The importance of galaxy collisions and mergers to the formation and evolution of galaxies has been clearly demonstrated by a variety of cosmological simulations (e.g. Cole et al. 2000). It is believed that a galaxy experiences a close encounter with another several times during its lifetime, from a merger involving two comparable mass galaxies (major merger) to less catastrophic events involving a smaller companion or a satellite (minor merger) (see Struck 1999, for a review). Cosmological simulations also show that hierarchical galaxy formation is an ongoing process even in the present epoch as evidenced by the ubiquitous presence of systems in the local universe that show signatures of major and minor mergers (e.g. Murali et al. 2002). Observations of the early universe conducted using sensitive sub-mm detectors suggest that collisions and mergers played important roles to the formation of stars and galaxies in the early epochs (Blain et al. 2002). Studying the colliding galaxy population in the local universe, therefore, is an important first step toward better understanding the process of galaxy formation and evolution and the star formation history in the universe.

Star formation requires an abundant supply of molecular gas. Studies of molecular gas (traced in CO) in the Milky Way has been done efficiently and extensively using single dish radio telescopes and interferometers. In extragalactic studies, extensive large scale surveys of molecular gas have been largely limited to single dish observations (see Young & Scoville 1991; Young et al. 1995). A beam that subtends a large area of the sky allows an efficient determination of the total amount of the emission, and hence the total molecular gas mass, in a relatively short amount of time. The resultant large database of hundreds of galaxies yields a statistically significant comparison of the physical properties in different Hubble types. A main shortcoming of these observations is the lack of spatial information resulting from the large beam sizes. Interferometric observations can significantly improve the resolution problem, but sparse sampling of the uv-space by the existing array telescopes operating at millimeter wavelengths generally suffer from poor surface brightness sensitivity and limited dynamic ranges ($\leq 10 - 20$). In addition, an extensive survey to develop a sample size comparable to those achieved by single dish experiments would take a prohibitively long time. Sakamoto et al. (1999) were the first to conduct an extensive interferometric survey of CO (1–0) emission in 20 nearby galaxies using the 6-element Nobeyama Array and the Owens Valley Radio Observatory (OVRO)[1] millimeter array. In a more recent survey using the Berkeley-Illinois-Maryland Association (BIMA) array (Helfer et al. 2003), 44 nearby late type galaxies were imaged at $\sim 6''$ resolution. Thus a growing database of high resolution CO (1–0) observations of nearby spiral galaxies is now available.

Single dish telescope surveys dedicated exclusively to measuring CO (1–0) emission in colliding disk systems have been carried out previously (Zhu et al. 1999; Gao & Solomon 1999; Georgakakis, Forbes & Norris 2000; Yao et al. 2003), but interferometric surveys of CO emission with good

[1]The Owens Valley Radio Observatory is operated by the California Institute of Technology.

spatial information are limited in number and in size. The H I emission in colliding galaxies has been studied both using single dish and interferometers, and the characteristics of the H I tidal tails has been used as an important diagnostics to trace the history of the interaction and star formation activity (e.g. Hibbard & van Gorkom 1996). The important next step, therefore, is to study the spatial distribution and the kinematics of dense and diffuse molecular ISM in colliding systems with the high resolution afforded by interferometers.

The response of the gas in a simulated disk-disk collision was investigated in detail by Iono, Yun & Mihos (2004, Paper I hereafter). It was found that stars respond to the tidal interaction by forming both transient arms and long lived $m = 2$ bars, but the gas response is more transient, flowing directly toward the central regions within about 10^8 years after the initial collision. Comparing the predicted inflow timescale (10^8 years) with the total merger timescale ($5-10\times10^8$ years) suggests that 10 - 20% of randomly selected interacting/merging systems in the local universe have a possibility to exhibit observable signature of radial inflow. The evolution of the structural parameters such as the asymmetry (A), the concentration (C) and the compactness (K) parameters were investigated, and the possible use of the K parameter and the molecular fraction (M_{H_2}/M_{gas}) to infer the merger chronology was suggested. It was shown that distinct emission features in the forbidden velocity quadrants of the position velocity diagram (PVD) identifies non-circular gas kinematics driven by the perturbation of the non-axisymmetric structure. These diagnostics tools developed using numerical simulation can be applied directly to observational data, and whether the same behavior is seen in observations is an important test concerning the validity of the physics implemented in the numerical simulations. To this end, this paper describes the observational data of 10 colliding systems in H I and CO (1–0) emission obtained using the Very Large Array (VLA)[2] and Owens Valley Radio Observatory millimeter array. Detailed statistical and comparative analysis of this data with a sample of nearby isolated systems can be found in our forthcoming paper (Paper III).

The organization of this paper is as follows. First, the sample selection is described in §2, followed by a description of the data reduction and calibration techniques in §3. Main results are presented and discussed in §4, §5, §6 and §7. Qualitative and quantitative descriptions of the individual sources are presented in §8. A short summary is given in §9.

2. Sample Selection

A significant amount of information pertaining to the interaction history can be obtained by examining the optical morphology alone. Bushouse (1986) compiled a set of $\sim$ 100 strongly interacting systems that involve two or more progenitor galaxies by visually inspecting the Uppsala

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[2]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

General Catalogue (UGC). He concluded that these systems show a systematically higher level of Hα luminosity and equivalent width than those found in isolated systems, but also found that about 30% of the interacting galaxies show weak or no optical emission lines much like the spectra of elliptical galaxies. A sub-set of 80 systems were further investigated by Zhu et al. (1999) in CO (1-0) using both the NRAO 12 m and the IRAM 30 m single dish radio telescopes. The interacting systems investigated in this study have been selected from the sample of Zhu et al. (1999) according to the following criteria:

1. **Major Mergers:** systems must include two nearly equal mass large spirals with $M_B \leq -19$,
2. **Projected Separation:** interacting pairs covering a wide range of separation, from 5 to 40 kpc, are chosen,
3. **Proximity:** sufficiently close ($\lesssim$ 100 Mpc) to be resolved with the OVRO resolution ($\sim 5'' =$ 2.4 kpc at D=100 Mpc),
4. **CO emission:** required $S_{CO} \geq 20$ Jy km s^{-1} to ensure clear detection by the interferometer.

Out of the 80 pairs in Zhu et al. (1999), eight pairs meet this selection criteria. Five sources (VV 48, VV 247, VV 769, VV 242, VV 244) were observed in CO (1–0) using the OVRO in Spring 2002, two sources (VV 246, VV 254) were observed during the 1997–1998 season, and the final source (VV 253) was observed in Spring 1995 and the data were retrieved from the OVRO archive. In addition to the eight sources selected from the Zhu et al. (1999) sample, three pairs that satisfy the same selection criteria (VV 219, VV 55, VV 254) were observed at the OVRO array. VV 219 was observed in Spring 2002, while both VV 55 and VV 254 were observed during the 1997–1998 season. Observation of VV 246 (NGC 3395/6) resulted in a non-detection by the interferometer, despite the reported flux of 58 Jy km s^{-1} (NGC 3395) and 39 Jy km s^{-1} (NGC 3396) obtained using the NRAO 12 m telescope (Zhu et al. 1999). The non-detection result of VV 246 is not presented here. This will comprise an interferometric CO (1–0) sample of a total of 10 pairs (or 20 galaxies)(see Table 1) – a large enough of a sample to allow the full examination of the large parameter space involved. Five of these sources (VV 55, VV 253, VV 242, VV 219, VV 244) were also observed in H I emission using the VLA in Winter 2002. The H I data for three sources (VV 48, VV 247, VV 731) were obtained from the VLA archive, while the maps of VV 254 and VV 769 were kindly supplied by J. Condon.

To place the characteristics of the sample sources in a broader context, a first order assessment of the merger chronology is performed by sorting the sample systems according to their projected nuclear separation (Table 1 and Figure 1). This classification scheme is similar to the method adopted by Toomre (1977, i.e. the Toomre Sequence) where eleven colliding/merging galaxy pairs from various stages of the interaction were selected from the NGC catalog, and the optical morphology of the pairs were used to roughly define the interaction sequence. Classifying the interacting galaxies in this way can introduce significant uncertainties because the sample sources are predominantly early to intermediate stage systems, whereas the Toomre sequence covers a much broader range of interacting systems from the early stage ("the Antennae (NGC 4038/9)") to the late stage merger ("Atoms for Peace (NGC 7252)"). This ordering will be revised in Paper III from a different perspective using a more comprehensive and quantitative set of analysis tools derived from the global properties in optical, CO (1–0) and H I emission.

In order to investigate the environment in which each galaxy pair resides, the projected 2 Mpc radius of each pair was searched for the presence of neighboring galaxies using the NASA/IPAC Extragalactic Database (NED)[3]. Constraining the velocity range according to the Hubble Law will only include sources in a narrow velocity space (i.e. $\Delta v = 150$ km s^{-1} for 2 Mpc using $H_0 = 75$ km s^{-1} Mpc^{-1}), and it will likely preclude galaxies with high peculiar velocities with respect to the Hubble flow. To be conservative, therefore, the adopted velocity range includes galaxies within $\Delta v = 500$ km s^{-1} of the systemic velocity. The results are presented in Table 2. The NED only includes galaxies that exist in previous survey catalogs and may not have the faint dwarf companions that past instruments were not capable of detecting due to sensitivity or coverage limitations. For example, the all sky 2MASS catalog (Jarrett et al. 2003) and the SDSS (Abazajian et al. 2003) has a sensitivity limit of $K_s = 13.5$ and $r = 22$, respectively. Excluding such faint undetected dwarf galaxies which are predicted to be abundant, half of the program sources (VV 55, VV 48, VV 253, VV 219, VV 244) appear to reside in a high density environment as the large number of neighboring sources indicates. VV 219 is an interacting system in the Virgo Cluster and therefore has an exceptionally large number of neighbors. The rest of the systems (VV 254, VV 247, VV 769, VV 242, VV 731) have about a factor of ten smaller number ($N \simeq 0 - 6$) of neighboring sources, which suggests that the evolution is determined mostly from the companion galaxy in the respective galaxy systems.

[3]This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Fig. 1.— DSS2 images of the sample sources arranged by decreasing projected nuclear separation. The horizontal bar drawn in each panel shows the physical scale of 10 kpc, with the angular size labeled in arc-seconds. The abscissa and ordinate are aligned with east-west and north-south directions respectively. See Keel & Borne (2003, Fig. 3) for a high resolution *HST* image of VV 247. The high quality *HST* image clearly shows the detailed structure of the nuclear regions as well as the ubiquitous dust lanes outlining the tidal tails. The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation, the National Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation.

Table 1. Interacting Galaxy Sample

Source	R.A.[a] (J2000)	Decl. (J2000)	Class.[b]	M_B[c]	z (D)[d] (Mpc)	sep.[e] (kpc)	$L_{(F)IR}$[f] ($10^{10}L_\odot$)	Ratio of L_B[g] (L_1/L_2)
VV 55					0.023 (90)	38	28.3 (15.1)	1.00
NGC 5257	$13^h39^m52.9^s$	$+00^d50^m24.5^s$	HII	-21.8				
NGC 5258	$13^h39^m57.7^s$	$+00^d49^m51.5^s$	HII/L	-21.7				
VV 48					0.012 (42)	26	6.1 (3.2)	1.07
NGC 5394	$13^h58^m33.7^s$	$+37^d27^m12.5^s$	···	-19.8				
NGC 5395	$13^h58^m37.9^s$	$+37^d25^m28.5^s$	···	-21.1				
VV 254					0.015 (55)	20	7.0 (3.6)	1.03
UGC 12914	$00^h01^m38.3^s$	$+23^d29^m01.2^s$	L	-21.2				
UGC 12915	$00^h01^m41.9^s$	$+23^d29^m45.2^s$	L	-20.6				
VV 253					0.033 (131)	18	32.3 (17.9)	···
NGC 5331N	$13^h52^m16.4^s$	$+02^d06^m31.5^s$	HII	-21.6				
NGC 5331S	$13^h52^m16.2^s$	$+02^d06^m04.5^s$	···	(total)				
VV 247					0.021 (81)	17	14.2 (7.6)	1.11
NGC 6621	$18^h12^m55.3^s$	$+68^d21^m48.5^s$	HII	-20.6				
NGC 6622	$18^h12^m59.6^s$	$+68^d21^m14.5^s$	···	-18.5				
VV 769					0.018 (67)	17	4.5 (2.4)	1.02
UGC 813	$01^h16^m16.5^s$	$+46^d44^m24.8^s$	···	-20.4				
UGC 816	$01^h16^m20.5^s$	$+46^d44^m52.8^s$	···	-20.9				
VV 242					0.016 (57)	13	7.1 (3.9)	1.00
UGC 11984	$22^h19^m27.8^s$	$+29^d23^m44.9^s$	···	-20.5				
UGC 11985	$22^h19^m30.3^s$	$+29^d23^m16.9^s$	···	-20.5				
VV 219					0.004 (16)[h]	11	2.2 (1.1)	1.03
NGC 4567	$12^h36^m32.7^s$	$+11^d15^m29.0^s$	···	-20.5				
NGC 4568	$12^h36^m34.3^s$	$+11^d14^m20.0^s$	···	-21.1				
VV 731					0.025 (98)	7	21.5 (13.6)	···
NGC 7592W	$23^h18^m21.8^s$	$-04^d24^m57.1^s$	HII	-21.1				
NGC 7592E	$23^h18^m22.6^s$	$-04^d24^m58.1^s$	···	(total)				
VV 244					0.007 (24)	5	2.2 (1.1)	1.01
NGC 5953	$15^h34^m32.4^s$	$+15^d11^m37.8^s$	L/S2	-19.2				
NGC 5954	$15^h34^m35.0^s$	$+15^d12^m00.8^s$	S2	-19.1				

[a]The source coordinates are found from the peak of the 2MASS K-band images. The resolution of the images is $2-3''$. Atlas Image obtained as part of the Two Micron All Sky Survey (2MASS), a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

[b]Spectral classification obtained from NED, where different letters correspond to; LINER (L), star forming (HII) and Seyfert 2 (S2).

[c]From RC3 when available, else from Georgakakis, Forbes & Norris (2000)(NGC 5331), Bushouse (1987)(NGC 6621/2), Zhu et al. (1999)(UGC 11984/5) and Soifer et al (1987)(NGC 7592).

[d]The redshift information is retrieved from NED. The luminosity distance is derived using the ΛCDM cosmology ($H_0 = 75$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$)

[e]Projected physical separation of the pair.

[f]The infrared and far infrared luminosities are derived from the IRAS 12, 25, 60 and 100μm flux in the *IRAS* Revised Bright Galaxy Sample (Sanders et al. 2003) for all of the systems except for VV 769 where the values from the Faint Source Catalogue (Moshir et al. 1990) is used. $L_{IR} = 4\pi D_L^2 F_{IR}$, where $F_{IR} = 1.26\times10^{-14}[13.48\ f_{12} + 5.16\ f_{25} + 2.58\ f_{60} + f_{100}]$

(Sanders & Mirabel 1996). The FIR luminosities are shown in () (Helou et al. 1988).

[g]Ratio of the absolute magnitudes in the pair should reflect the relative masses (assuming a constant mass-to-light ratio). Values for VV 253 and VV 731 are not available because B-band magnitudes are available only for the whole systems.

[h]The redshift of VV 219 in NED is given as $z = 0.0075$ (or $D = 28$ Mpc), but the redshift of the giant elliptical galaxy at the center of the Virgo cluster M87 is given as $z = 0.0044$ (or $D = 16$ Mpc). The discrepancy may be due to the high peculiar velocity of VV 219 in the cluster potential. Because VV 219 and M87 are located well within a projected distance of 1 Mpc, we adopt $z = 0.0044$ (or $D = 16$ Mpc) for the redshift of VV 219.

3. Observations and Data Reduction

3.1. H I

The H I observations for five of the sources (VV 55, VV 253, VV 242, VV 219, VV 244) were carried out at the VLA in Winter 2002 using the C configuration. The correlator was configured to use 2 IFs with 3.125 MHz total bandwidth and 48.8 kHz (10.5 km s^{-1}) frequency resolution after on-line Hanning smoothing. The on-source integration time for each source was $\sim$ 5 hours. A nearby quasar was observed every 30-40 minutes to track the gain variation. The flux and passband calibrations were performed by observing the bright standard flux calibrators 3C 48 (16.5 Jy at 1.4 GHz) or 3C 286 (15.0 Jy at 1.4 GHz). The calibration and imaging were carried out using the NRAO software system AIPS. Natural weighting (ROBUST = 5) of the visibility data was adopted to maximize the sensitivity for the imaging. Key details of the observations are summarized in Table 3.

3.2. CO (1–0)

The CO (1–0) observations for six of the sources (VV 48, VV 247, VV 769, VV 242, VV 219, VV 244) were carried out using the OVRO interferometer array during the Spring 2002 season. Two antennas were configured in the north-south direction with a 50 m baseline length while four antennas with baseline lengths between 15 and 115 m were assigned in the east-west direction (the L configuration). The digital correlator was configured to cover 480 MHz in 4 modules, each divided into 120 channels giving a velocity resolution of $\sim$ 10.5 km s^{-1}. One or more bright quasars such as 3C 84, 3C 273, or 3C 454.3 were observed in each track for the passband calibration. The absolute flux scale is based on the observations of Uranus. A nearby quasar selected for each target source was observed every 20 minutes to track the short term gain variation, and amplitude and phase fittings were performed using baseline based calibration. The data were reduced using the OVRO data reduction program MMA (Scoville et al. 1993). The calibrated data were imaged and deconvolved using the program DIFMAP (Shepherd et al. 1994). Two narrow band channels were averaged to produce a natural weighted CLEANed data cube at a final velocity resolution of 21 km s^{-1}. For sources with low S/N, a Gaussian taper was applied in the uv-space to smooth the data spatially. For sources with high S/N, uniform weighting was used to improve the angular resolution. Key details of the observations are summarized in Table 4.

4. Derived Properties of Atomic and Molecular Gas

The derived quantities from the H I and CO (1–0) observations are summarized in Table 5 and 6 respectively. The properties of H I were derived for the whole system, rather than trying to separate the H I into two galaxies. Table 5 has the following format.

Table 2. Galaxies Within 2 Mpc Volume Around the Sample Sources

Source	cz[a] (km s^{-1})	No. of sources	Nearby Source[b]	Projected Distance (kpc)	v (km s^{-1})
VV 55	6777 ± 500	12	USGC U556	233	6785
			IC 904	709	6752
			WBL 460	715	6805
			CGCG 017-046	757	6754
			2dFGRS N335Z175	825	6727
VV 48	3481 ± 500	23	USGC U585	148	3286
			[FK2002] 207	159	3270
			NGC 5380	263	3173
			NGC 5395	303	3290
			NGC 5378	354	3042
VV 254	4353 ± 500	6	KUG 2357+228	515	4461
			UGC 24	1035	4442
			KUG 0003+235	1085	4574
			UGC 11	1379	4447
			NGC 9	1632	4528
VV 253	9906 ± 500	17	[WZX98] 13496+0221C	0	9833
			CGCG 017-081	19	9766
			WBL 471	50	9926
			USGC U572	240	9787
			2MASX J13513864+0209279	324	9650
VV 247	6329 ± 500	1	UGC 11183	544	6164
VV 769	5266 ± 500	1	CGCG 551-011	43	5373
VV 242	4531 ± 500	1	CGCG 494-017	807	4583
VV 219	2265 ± 500	58	IC 3509	478	2000
			NGC 4607	636	2257
			IC 3562	654	2051
			NGC 4569	666	1870
			VCC 1919	770	1869
VV 731	7327 ± 500	0	···	···	···
VV 244	1962 ± 500	20	UGC 9902	25	1696
			KTG 62	54	1906
			NGC 5951	114	1780
			NGC 5962	321	2040
			UGC 9951	491	2004

[a]The redshifts listed in Table 1 are converted to velocity, and the search radius includes galaxies within ± 500 km s^{-1} of this velocity

[b]The source database includes the standard catalogs such as the NGC and UGC, as well as the more recent deep surveys such as the 2MASS (Jarrett et al. 2003) and SDSS (Abazajian et al. 2003), which contains galaxies brighter than $K_s = 13.5$ and $r = 22$, respectively. The closest five sources are listed here if the number of sources is greater than five.

Table 3. VLA Observational Properties

Source	Date	Config.	σ_{RMS}[a] (mJy)	Beam[b] ($''$)	Beam (kpc)	Calibrator
VV 55	Winter 2002	C	0.18	22.2 × 17.6	9.8 × 7.8	J1354−021
VV 48	Summer 1993	C,D	0.79	17.8 × 16.3	4.0 × 3.6	J1504+377
VV 254	Fall 1990	C	· · ·	18.0 × 18.0	5.1 × 5.1	J2330+110
VV 253	Winter 2002	C	0.22	22.0 × 17.1	14.2 × 11.0	J1354−021
VV 247	Winter 1998	CnB	0.57	16.2 × 13.0	6.5 × 5.2	J2236+284
VV 769	Spring 2001	B,C	0.23	16.3 × 16.3	5.7 × 5.7	J0114+483
VV 242	Winter 2002	C	0.18	17.9 × 17.6	5.5 × 5.4	J1252+119
VV 219	Winter 2002	C	0.86	19.9 × 14.0	1.6 × 1.1	J1252+119
VV 731	Summer 1987	D	1.95	128.6 × 82.6	35.5 × 22.8	J2253+161
VV 244	Winter 2002	C	0.29	19.8 × 17.9	2.3 × 2.1	J1520+202

[a]The RMS noise per 11 km s^{-1} channel, except for VV 731 where 21 km s^{-1} velocity resolution was used. Data for VV 254 and VV 769 were provided by J. Condon (Condon et al. 1993; Condon, Helou & Jarrett 2002), and the noise properties for VV 254 is unknown because the map was clipped at a threshold value.

[b]The synthesized beam size recovered using natural weighting (ROBUST = 5).

Col. (1) Name of the pair from the Vorontsov-Velyaminov catalog (Vorontsov-Velyaminov 1959, 1977)

Col. (2) Recovered integrated flux derived from the moment zero map. The AIPS task MOMNT was used to generate the moment zero map.

Col. (3) Total atomic gas mass calculated assuming an optically thin emission, $M_{HI}(M_\odot) = 2.36 \times 10^5 D^2 \int S_\nu dv$ where D is distance in Mpc and $\int S_\nu dv$ in Jy km s^{-1}. The integrated flux ($\int S_\nu dv$) given in Col. (2) is used.

Col. (4) Peak brightness temperature.

Col. (5) Peak column density.

Col. (6) Total line width in Full Width Zero Intensity (FWZI).

Table 6 has the following format:

Col. (1) Name of the pair from the Vorontsov-Velyaminov catalog (Vorontsov-Velyaminov 1959, 1977) and the UGC/NGC number for each individual galaxy.

Col. (2) Recovered integrated flux derived from the moment zero map. The AIPS task MOMNT was used to generate the moment zero map. Single dish measurements from Zhu et al. (1999) are listed for comparison in () when available.

Col. (3) Derived total molecular gas mass from the integrated flux in Col. (2) when available. The Galactic CO to H_2 conversion ($M_{H_2}(M_\odot) = 1.18 \times 10^4 D^2 \int S_{CO(1-0)} dv$, where D is distance in Mpc and $\int S_{CO(1-0)} dv$ is the integrated interferometer flux in Jy km s^{-1}) was used.

Col. (4) Dynamical mass derived from the maximum radial extent of the CO (1–0) emission and the observed velocity maxima. Inclination correction is not applied.

Col. (5) Peak brightness temperature.

Col. (6) Peak H_2 column density.

Col. (7) Average surface density given by $M_{H_2}/\pi R^2 ln(2)$, where R is the FWHM of the deconvolved size of the emission.

Col. (8) Systemic velocity derived from the median velocity of the CO (1–0) spectrum.

Col. (9) Estimated total line width in Full Width Zero Intensity (FWZI).

Col. (10) Ratio of molecular mass to dynamical mass. Note that M_{dyn} is not corrected for the inclination.

Col. (11) Ratio of molecular gas to total gas mass. The total gas mass is the sum of atomic (from Table 5) and molecular gas (from Col. (3)) for the whole system.

Col. (12) Star formation efficiency (L_{IR}/M_{H_2}). The molecular gas mass derived from the interferometer in Col. (3) is used.

Table 4. OVRO Observational Properties

Source	σ_{RMS} [a] (mJy)	Beam[b] ($''$)	Beam (kpc)	Calibrator
VV 55	16	6.2 × 3.7	2.7 × 1.6	J1256−057
VV 48	16	5.5 × 4.3	1.2 × 1.0	J1153+495
VV 254	15	7.2 × 5.1	2.0 × 1.4	J2253+161
	(20)	(4.3 × 3.4)	(1.2 × 1.0)	···
VV 253	11	5.4 × 4.4	3.5 × 2.8	J1256−057
VV 247	24	6.6 × 5.6	2.7 × 2.3	J1800+784
VV 769	16	5.1 × 4.1	1.8 × 1.4	J0136+478
VV 242	11	4.4 × 3.1	1.3 × 0.9	J1549+026
VV 219	12	4.0 × 3.5	0.3 × 0.3	J1549+026
VV 731	10	4.5 × 3.6	2.2 × 1.7	J2246−121
VV 244	15	4.4 × 3.6	0.6 × 0.5	J1549+026

[a]The RMS noise per 21 km s^{-1} channel

[b]The synthesized beam size recovered using natural weighting, except for VV 254 where uniform weighting was also adopted in order to increase the resolution (shown in ()).

Table 5. Derived H I Properties

Source	$S_\nu dv$ (Jy km s^{-1})	$\log M_{HI}$ ($M_\odot$)	ΔT_{peak} (K)	$\log N_{peak}$ (cm^{-2})	ΔV_{ZI} (km s^{-1})
VV 55	17.6	10.5	7.9	21.4	475
VV 48	13.8	9.8	20.3	21.6	620
VV 254[a]	14.0	10.1	12.4	21.5	721
VV 253	4.8	10.3	29.0	21.3	573
VV 247	2.6	9.6	10.5	21.3	518
VV 769[b]	9.4	10.1	9.4	21.6	854
VV 242	11.5	10.1	21.9	21.7	447
VV 219	21.1	9.1	29.8	21.5	335
VV 731	0.8	9.2	2.6	19.8	87
VV 244	7.9	9.0	71.1	21.4	365

[a]Condon et al. (1993)

[b]Condon, Helou & Jarrett (2002)

Table 6. Derived CO(1–0) Properties

Source	$S_\nu dv$[a] (Jy km s^{-1})	$\log M_{H_2}$ ($M_\odot$)	$\log M_{dyn}$ ($M_\odot$)	ΔT_{peak} (K)	$\log N_{peak}$ (cm^{-2}($M_\odot$ pc^{-2}))	Σ ($M_\odot$ pc^{-2})	v_{sys} (km s^{-1})	ΔV_{ZI} (km s^{-1})	$\frac{M_{H_2}}{M_{dyn}}$	$\frac{M_{H_2}}{M_{gas}}$ b	$\frac{L_{IR}}{M_{H_2}}$ ($L_\odot$ $M_\odot^{-1}$)
VV 55										0.52	7.8
NGC 5257	137	10.1	10.5	0.6	22.5 (471)	108	6764	545	0.46		
NGC 5258	250	10.4	11.0	1.1	22.6 (622)	141	6775	479	0.22		
VV 48										0.49	7.6
NGC 5394	148 (201)	9.5	9.3	2.1	22.8 (1021)	189	3444	150	1.74		
NGC 5395	171 (548)	9.6	11.2	0.3	22.0 (168)	68	3508	533	0.02		
VV 254										0.60	3.6
UGC 12914	163 (420)	9.8	11.0	0.7	22.3 (296)	71	4330	600	0.06		
UGC 12915	334 (381)	10.1	10.8	1.4	22.6 (681)	106	4502	645	0.18		
VV 253										0.63	6.4
NGC 5331N	17 (66)	9.5	···	0.3	22.2 (225)	86	9860	440	···		
NGC 5331S	150 (134)	10.5	11.4	0.7	23.0 (1401)	328	9920	690	0.13		
VV 247										0.9	7.1
NGC 6621	369 (219)	10.5	10.6	0.7	22.7 (815)	150	6164	455	0.72		
NGC 6622	··· (34)	···	···	···	···	···	···	···	···		
VV 769										0.28	8.7
UGC 813	27 (43)	9.2	10.1	0.4	22.2 (242)	83	5159	345	0.11		
UGC 816	60 (161)	9.5	10.7	0.6	22.2 (256)	73	5320	367	0.07		
VV 242										0.38	8.9
UGC 11984	172 (180)	9.8	10.7	0.7	23.0 (1654)	255	4577	451	0.14		
UGC 11985	··· (32)	···	···	···	···	···	···	···	···		
VV 219										0.64	2.7
NGC 4567	121	8.6	9.5	1.2	22.2 (213)	189	2285	169	0.12		
NGC 4568	642	9.3	10.6	2.7	22.8 (960)	426	2232	317	0.05		
VV 731										0.89	15.8
NGC 7592W	59	9.8	9.9	0.8	22.7 (714)	170	7353	416	0.78		
NGC 7592E	59	9.8	10.5	0.8	22.6 (610)	91	7342	416	0.24		
VV 244										0.68	8.0
NGC 5953	233 (365)	9.2	9.7	2.1	22.7 (706)	201	1968	254	0.35		
NGC 5954	108 (73)	8.9	9.5	1.2	22.5 (512)	101	1984	253	0.21		

[a]Single dish measurements from Zhu et al. (1999) are shown for comparison in () when available. All of the single dish data were obtained at the NRAO 12 m telescope, except for VV 253 where the IRAM 30 m telescope was used. In addition, a fully sampled map of VV 247 using the IRAM 30 m is presented in Zhu et al. (1999), and this flux measurement is consistent with the sum of the fluxes of the pair obtained using the NRAO 12 m (see text).

[b]The molecular gas mass fraction. $M_{gas} = M_{H_2} + M_{HI}$.

4.1. Flux Recovery and Derivation of Molecular Gas Mass

The main advantage of interferometry is its ability to produce high angular resolution images, thereby allowing the investigation of gas on sub-kpc to kpc scales for nearby sources. However, spatial filtering by interferometers can lead to erroneous maps at large scales that could in turn profoundly mislead the observational interpretation of sources when much of the low surface brightness features are resolved out (Wilner & Welch 1994). One can estimate the amount of missing flux by comparing the derived total flux to that of published results (if available).

In many cases, the OVRO observations did not agree well with the flux measurements reported earlier by Zhu et al. (1999) (see Table 6). Flux recovery is as low as 30% in NGC 5395 and as high as 170% in NGC 6621 with an average of 82%. Assuming the minimum projected baseline length is the diameter of the dish (i.e. $\sim$ 10 m), the largest detectable structure is about $50''$. This may impact some of the sources where the OVRO primary beam barely covers the entire extent of sources such as VV 219 and VV 254. In three cases (NGC 6621, NGC 5331S and NGC 5954) the interferometer flux exceeds the single dish measurements. The discrepancy in NGC 5331S and NGC 5954 are of order 40% and could be attributed to the uncertainties in the (1) the amplitude calibration, (2) the baseline fitting for single dish measurements, and (3) the Gaussian (or exponential) correction factor adopted by Zhu et al. (1999) in order to estimate the flux outside the beam. The interferometer flux in NGC 6621 is 70% higher than the single dish measuments by Zhu et al. (1999) where they recovered an integrated flux of 254 ± 29 Jy km s^{-1} from their fully sampled map obtained using the IRAM 30 m telescope. The origin of the apparent discrepancy between the single dish and the interferometer is unclear. It may be attributed to the uncertainties in the amplitude calibration, or to spurious features in the interferometer map due to the uncertainties in gain calibration or potential erroneous data that were undetected during data editing. Regardless of the underlying cause for the discrepancy, it is imperative to bear in mind that spatial filtering always exists in interferometric data, and interpretation of the qualitative and quantitative analysis should be treated with caution. Another possible source of uncertainty is the use of the Galactic CO-H_2 conversion to estimate the molecular gas mass. It has been suggested that the Galactic CO-H_2 conversion can overestimate the molecular gas mass by as large as factor 4 - 5 (Scoville, Yun, & Bryant 1997; Downes & Solomon 1998) in the nuclear starburst regions in LIRGs/ULIRGs. Many of our sample systems are undergoing moderate star formation activity (2-30 $M_\odot$ yr^{-1}). However, it is shown in § 6 that the CO emission is not as concentrated in the nuclear region as in LIRGs/ULIRGs, and therefore the use of the standard conversion is likely relatively safe here.

4.2. Brightness Temperature

The observed brightness temperature for the H I emission is related to the spin temperature by the optical depth and filling factor as $T_B = fT_S[1 - e^{-\tau}] \approx fT_S\tau$ for $\tau \ll 1$. It is possible that an edge-on galaxy could appear to have a larger optical depth than a face-on galaxy due to a longer line of sight. However, since the above measurement relies on the peak flux obtained in a narrow velocity channel, the optically thin approximation should hold true and will not introduce significant uncertainties in the derived temperature. The emission emerging from a narrow velocity channel can be comprised of blended emission from several overlapping H I cloud components with different temperature. The estimated spin temperature of $T_s \sim 100$ K in a simple 3-cloud model is relatively insensitive to the adopted cloud densities in the optically thin limit (see Appendix). This implies that in the optically thin limit and a peak brightness temperature of (10 – 20) K (Table 5), the product τf is $\sim (0.1 - 0.2)$. A beam filling factor close to unity will result in $\tau \sim (0.1 - 0.2)$, whereas a beam filling factor of 10% gives $\tau \sim (1-2)$, implying moderate opacity. It is also possible that the true spin temperature of these systems is higher than the above prediction because of a larger possible contribution from a non-thermalized H I cloud.

For the CO (1–0) emission which is optically thick under most astrophysical conditions, the peak emission in the channel maps can be translated into a peak brightness temperature through the use of the standard Rayleigh-Jeans approximation (Table 6). The filling factor of CO (1–0) emission is largely uncertain and the true brightness temperature directly scales with the product of filling factor and excitation temperature (i.e. $T_B \sim fT_{ex}$ where f is the beam filling factor). Assuming a beam filling factor of 0.1, the measured CO (1–0) brightness temperatures of 0.5 – 2 K suggest excitation temperatures of 5 – 20 K.

5. Atomic and Molecular Gas Mass

The atomic gas mass ranges from $1.8 \times 10^9 M_\odot$ to $3.4 \times 10^{10} M_\odot$ - a range of over one order of magnitude between the collision of two low mass galaxies (VV 244) and the massive major merger of VV 55 (Figure 2 (*top*)). The molecular gas mass is similarly diverse, ranging between $7.4 \times 10^8 M_\odot$ and $4.5 \times 10^{10} M_\odot$ (Figure 2 (*bottom*)). The large difference in M_{H_2} can be explained by the previously known correlation between the size of the optical galaxy and the molecular disk ($L_B \propto M_{H_2}^{0.72\pm0.03}$)(Young et al. 1989); i.e. in general, a larger stellar mass yields a larger molecular gas mass. On the other hand, the H I mass correlates poorly with L_B, possibly because a variety of morphological types are included in the sample. It has been well known that the M_{HI}/L_B ratio varies along the Hubble sequence (Roberts 1969).

The ratio L_{IR}/M_{H_2} is often used to infer the star formation efficiency (SFE), with average values from 12 $L_\odot/M_\odot$ in isolated systems with small variation along Hubble types to 78 $L_\odot/M_\odot$ in mergers (Young et al. 1986) and some as high as a few hundred (Young et al. 1989). The $SFEs$ derived from Hα emission show similar results (Young et al. 1996). Using a sample of 93 galaxies,

Fig. 2.— Distribution of atomic (*top*) and molecular (*bottom*) gas mass derived from HI and CO (1–0) observations respectively.

Solomon & Sage (1988) found that the $SFEs$ in "interacting pairs" (i.e. early stage mergers) are comparable to those derived in isolated systems, suggesting the need for "strong interactions" (i.e. late stage mergers) to increase the SFE. They further note that their mean L_{FIR}/L_{CO} ratios are about a factor of 2 smaller than those calculated from the $SFEs$ listed in Young et al. (1986), citing differences in the methods to determine the single dish CO luminosities as the primary reason for the observed discrepancies. The $SFEs$ in our sample are not particularly high ($L_{IR}/M_{H_2} = 2.7 - 15.8\ L_\odot/M_\odot$ or $L_{FIR}/M_{H_2} = 1.4 - 8.7\ L_\odot/M_\odot$; see Table 6), and they are generally similar to those derived for the isolated and weakly interacting galaxies in Solomon & Sage (1988, types 0, 1 & 2 in their classification). This is a further confirmation that galaxy interaction alone cannot raise the SFE, and more catastrophic events such as a coalescence of two galaxies is needed. There exist, however, systems with large $SFRs$ despite their large projected nuclear separation (Trung et al. 2001).

The molecular gas mass fraction (M_{H_2}/M_{gas}) may determine whether the underlying dynamical process has a significant effect on the phase transition of the cold gas from atomic to molecular (i.e. Mirabel & Sanders 1989). In the present sample, 70% of the sources have higher molecular gas mass than atomic gas, and this may be an indication that molecules dominate in colliding systems. Past single-dish surveys that included a variety of galaxy morphologies have failed to reach a unified conclusion – it is unclear whether tidal interaction plays a significant role in the phase transition (e.g. Horellou, Booth & Karlsson 1999). It is speculated that the primary discrepancy arises from the uncertainties pertaining to the single dish H I and CO (1–0) flux measurements, as well as to the validity of the Galactic CO – H_2 conversion factor. Detailed analysis and discussion of the relationship between the H I and H_2 gas mass content in various stages of the interaction will be presented as one of the main topics in Paper III.

6. Distribution and Kinematics of Atomic and Molecular Gas

The CO (1–0) and H I velocity integrated line intensity maps overlaid on the DSS R-band images are presented in Figures 3 – 12 (see Table 7 and 8 for the contour and gray scale level). The maps of the mean velocity overlaid over the velocity dispersion are also presented alongside to the velocity integrated line intensity maps. The general features seen in these maps are discussed first, followed by a more detailed discussion of the individual sources in section §8.

Table 7. H I Figure Properties

Source	Min Contour (cm^{-2})	Max Contour (cm^{-2})	Step (cm^{-2})	Vel. Step (km s^{-1})	Gray Scale (km s^{-1})
VV 55[a]	2.0×10^{20}	1.0×10^{21}	2.0×10^{20}	50	0 - 130
	1.0×10^{21}	2.6×10^{21}	4.0×10^{20}		
VV 48	2.0×10^{20}	1.0×10^{21}	2.0×10^{20}	50	0 - 90
	1.0×10^{21}	3.8×10^{21}	4.0×10^{20}		
VV 254	2.0×10^{20}	2.6×10^{21}	4.0×10^{20}	50	0 - 200
VV 253	2.0×10^{20}	1.0×10^{21}	2.0×10^{20}	50	0 - 120
	1.0×10^{21}	2.2×10^{21}	4.0×10^{20}		
VV 247	2.0×10^{20}	2.0×10^{21}	2.0×10^{20}	25	0 - 75
VV 769	2.0×10^{20}	4.0×10^{21}	4.0×10^{21}	50	0 - 170
VV 242	2.0×10^{20}	1.0×10^{21}	2.0×10^{20}	50	0 - 160
VV 219	2.0×10^{20}	1.0×10^{21}	2.0×10^{20}	50	0 - 37
	1.0×10^{21}	2.6×10^{21}	4.0×10^{20}		
VV 731	1.0×10^{19}	7.0×10^{19}	1.0×10^{19}	50	0 - 16
VV 244	2.0×10^{20}	2.2×10^{21}	2.0×10^{20}	25	0 - 60
	1.0×10^{21}	6.0×10^{21}	8.0×10^{20}		

[a]The contour steps are increased in the inner regions ($> 10^{21}$) of some of the galaxies for better visual appearance of the figures.

Table 8. CO Figure Properties

Source	Min Contour (cm^{-2})	Max Contour (cm^{-2})	Step (cm^{-2})	Vel. Step (km s^{-1})	Gray Scale (km s^{-1})	Position Angle (Degrees)
NGC 5257	2.0×10^{21}	2.8×10^{22}	4.0×10^{21}	50	0 - 130	270
NGC 5258	2.0×10^{21}	3.4×10^{22}	4.0×10^{21}	50	0 - 95	223
NGC 5394[a]	4.0×10^{21}	1.0×10^{22}	2.0×10^{21}	25	0 - 40	0
	1.0×10^{22}	6.0×10^{22}	4.0×10^{21}			
NGC 5395	2.0×10^{21}	1.4×10^{22}	4.0×10^{21}	50	0 - 40	0
UGC 12914	4.0×10^{21}	3.6×10^{22}	4.0×10^{21}	50	0 - 80	332
UGC 12915	4.0×10^{21}	3.0×10^{22}	4.0×10^{21}	50	0 - 150	307
NGC 5331	2.0×10^{21}	1.0×10^{22}	2.0×10^{21}	100	0 - 170	323
	1.0×10^{22}	6.0×10^{22}	8.0×10^{21}			
NGC 6621	2.0×10^{21}	4.6×10^{22}	2.0×10^{21}	50	0 - 114	309
UGC 813	4.0×10^{21}	3.6×10^{22}	4.0×10^{21}	50	0 - 45	315
UGC 816	4.0×10^{21}	1.6×10^{22}	2.0×10^{21}	50	0 - 50	0
NGC 7253	4.0×10^{21}	4.4×10^{22}	4.0×10^{21}	25	0 - 65	237
NGC 7254	4.0×10^{21}	3.0×10^{22}	4.0×10^{21}	25	0 - 37	354
NGC 4567	4.0×10^{21}	3.6×10^{22}	4.0×10^{21}	50	0 - 30	280
NGC 4568	1.0×10^{21}	6.0×10^{22}	4.0×10^{21}	50	0 - 45	204
NGC 7592	2.0×10^{21}	1.0×10^{22}	2.0×10^{21}	50	0 - 110	221 (257)[b]
	1.0×10^{22}	6.0×10^{22}	4.6×10^{21}			
UGC 11984	2.0×10^{21}	1.0×10^{22}	2.0×10^{21}	50	0 - 80	296
	1.0×10^{22}	8.2×10^{22}	8.0×10^{21}			

[a]The contour steps are increased in the inner regions ($> 10^{22}$) of some of the galaxies for better visual appearance of the figures.

[b]() for NGC 7592E

6.1. H I and CO Morphology

The summary of H I and CO (1–0) morphological properties in Table 9 highlights some of the distinct features seen in the maps presented in Figures 3 - 12. Specifically, we identify systems with visual signature of (1) a long H I tail, (2) substantial H I emission in the medium between the galaxies in the pair, (3) an offset between H I peaks and the stellar light, (4) an offset between CO (1–0) peaks and the galaxy center traced in K-band emission, and (5) an isolated CO (1–0) emission with no apparent optical counterpart. A short discussion of each feature and the galaxies identified are presented in what follows.

N-body simulations of galaxy interactions suggest that ejection of cold disk gas at large radii, primarily neutral hydrogen, into tidal tails is a ubiquitous phenomenon. The degree of ejection depends crucially on the encounter geometry (see Toomre & Toomre 1972). Tidal ejection is expected to occur to some degree even in an orbital geometry that is the least favorable to transfer energy and angular momentum (i.e. a retrograde encounter). Long and well defined tidal tails are unlikely to form in such an event. Inspecting the size and the amplitude of the tidal tails, therefore, offers a unique way to infer the orbital geometry (Hibbard & van Gorkom 1996). Out of the nine systems with high quality H I maps, five (VV 55, VV 253, VV 247, VV 731, VV 244) display long H I tidal tails (i.e. $D_{HI}/D_{25} > 1$) suggesting that at least one of the disks involved is in a prograde orbit (Table 9). The highly inclined geometry complicates the analysis in VV 242 despite hints of H I tails seen at the edges of both disks. It is not surprising to find that about 50% of the sources are in a prograde orbit since there are two equally possible disk orientations, unless the encounter geometry is such that it is a head-on collision similar to the "Cartwheel galaxy (VV 784)".

The occurrence of a long H I tail appears to coincide with the elevated level of infrared emission – out of the five systems with long H I tails, four (80%) are classified as LIRGs. Correlation between other morphological properties with infrared activity appears to be relatively insignificant (see Table 9). A strong perturbation from a prograde orbit can lead to efficient ejection of the outer disk gas into tidal tails, while the inward propagating waves can compress and heat the inner disk gas, simultaneously inducing intense star formation activity there. While the presence of a long H I tail may infer the interaction history and the increased bursts of star formation in a collision of gas-rich progenitor galaxies, it is possible that the strength of the interaction and the associated infrared activity are correlated with other important physical parameters. These include, for example, the temperature of the dust (Xilouris et al. 2004) and/or the presence of the nuclear AGN. It is, however, suggested that AGN dominated galaxies constitute only of order (1–2)% of the infrared luminous galaxy population (Yun, Reddy & Condon 2001). Further discussion on this apparent correlation will be conducted in Paper III.

Fig. 3.— Top: H I map of VV 55. Middle: CO (1–0) map of NGC 5257. Bottom: CO (1–0) map of NGC 5258. The corresponding mean velocity field is plotted in contours over the velocity dispersion map in gray scale on the right panel. See Table 7 and 8 for the contour levels

A recent, strong head-on collision can lead to a substantial amount of radio continuum emission in the medium between the two galaxies as seen in the two Taffy systems (see §7, §8.3, §8.6). A long stretched morphology is also seen in the H I emission in these galaxies. Therefore, substantial H I emission in the medium between the two galaxies may signify a strong and recent encounter. By searching for systems in which the $N_{\rm HI} = 10^{21}$ cm^{-2} contours are connected between the two galaxies, nearly 80% (7/9) of the systems show visual evidence of such feature. This may be a slight overestimate as the line of sight projection can significantly impact the apparent H I morphology in some cases (i.e. VV 242, VV 244). In Paper III, this feature will be used as one of the important criteria to define the merger chronology of the sample.

A transient and inelastic response of the gas is particularly noticeable during the initial stages of a disk-disk collision in numerical simulations, sometimes resulting in a strong asymmetry in the gas distribution (see Paper I). In addition to the displacement of the CO peaks from the stellar light (see below), a significant displacement of H I peaks from the stellar disks is also seen among six (VV 244, VV 247, VV 253, VV 254, VV 731 and VV 769) of the systems. Such displacements are generally not expected since gas and stellar structures inside the tidal radius should remain unaffected by a tidal disruption. A pre-existing asymmetry or a central hole in the gas distribution prior the recent collision may account for the observed displacement in some cases. An inelastic gaseous collision is primarily responsible for the gas morphology in the two "Taffy" systems (VV 254 and VV 769), and it may play an important role in shaping the gas distribution in many of the other systems as well.

In general, a smooth and continuous distribution of CO (1–0) in the disk is seen, but clumpy distributions are evident in a few sources that are gas poor (UGC 12914, UGC 816, NGC 4567, NGC 5395). CO (1–0) emission is fully resolved spatially with at least 3 synthesized beams across the stellar disks in all cases, widely extended with respect to the R-band emission at the column density of 2.0×10^{21} cm^{-2}. This is in a stark contrast to the observations of IR luminous, more advanced interaction/merger systems whose CO emission is typically characterized by a compact (≤ 1 kpc) nuclear concentration centered on the local minima in gravitational potential (Scoville, Yun, & Bryant 1997; Downes & Solomon 1998; Bryant & Scoville 1999; Yun & Hibbard 2001).

The peak of the CO (1–0) emission does not coincide with the dynamical center of the galaxy determined from K-band emission in NGC 5395, NGC 5258, UGC 12914, or NGC 5331N. There are five CO emitting complexes with no optical counterpart (UGC 12914, UGC 816, NGC 5331S, NGC 5954 and NGC 6621). The true nature of these complexes is yet to be determined, but one possible explanation is the ejection of molecular gas from strong gas-gas collisions during the first pericentric passage.

Finally, the galaxy environment seems to play a relatively minor role in the formation and the shaping of the long H I tails. While previous H I observations with much lower surface brightness

Fig. 4.— Same as Figure 3 but for VV 48.

sensitivity have shown that galaxies in a dense cluster environment harbor less extended atomic gas than galaxies in isolation (Cayatte et al. 1990), such pattern is not obvious in the current data (i.e. long tidal tails are seen independent of the environment, with a possible exception of VV 219 in Virgo). Similarly, whether the environment affects the distribution and the physical properties of the CO (1–0) emitting clouds is uncertain from our data.

6.2. Position Velocity Diagrams

The Position Velocity Diagram (PVD) is a commonly used tool for inferring the gas kinematics and the rotation of galaxies. The KPVSLICE routine in KARMA (Gooch 1995) allows interactive construction of the PVDs using a 3 dimensional datacube as an input. The coordinates of the K-band emission peak was used to align the center of the PVD slit (see Table 1), which was then rotated interactively until the slit position angle matched the apparent kinematic major axis. For consistency, the position angle of the slit was chosen to lie in the eastern half for every galaxy, and thus the orientation of the resulting PVDs are different depending on the direction of the disk rotation along the line of sight.

The results are shown in Figure 13 - 15, and the adopted position angles listed in Table 8. The morphology of the CO (1–0) PVDs varies significantly depending on the amount of disk gas, spatial resolution, and the presence of tidally induced non-circular motion dominating both the inner and the outer parts of the interacting galaxies. The dominance of symmetric morphology in the PVDs among nearby isolated galaxies (see Sakamoto et al. 1999) contrasts strongly with the CO (1–0) PVDs shown in Figure 14 - 15 where about one half are asymmetric with respect to the dynamical center. A close examination of the H I and CO (1–0) PVDs reveals that the peak of the emission is radially offset toward one or both directions from the PVD centroid (K-band peak) in many cases. Absorption can affect the observed H I distribution to some degree, but opacity effect is less important for CO (1–0). Among the PVDs that display smooth and continuous CO (1–0) distribution with high enough S/N, more than 50% (NGC 4567/8, NGC 5953/4, NGC 7592, and UGC 12914/5) show this anomalous kinematic signature in CO (1–0) emission. The simulation analysis presented in Paper I suggests that a central depression in the molecular gas emission and the displacement of the emission peak may indicate the existence of a central gas ring or tightly wound spiral arms. The existence of periodic orbits (or a stellar bar) is one possible explanation for the formation of a central ring. Such a structure does not directly imply gas inflow, but it suggests that gas orbits possess axial symmetry such as a ring or "twin peaks" (Kenney et al. 1992) on kpc scales. Using images with angular resolution that is a factor of a few better (Sakamoto et al. 1999), these peculiar structures were found to dominate the kinematics in some of the isolated galaxies on scales of few hundred parsecs. Angular resolution limitations may affect the interpretation of these

Fig. 5.— Same as Figure 3 but for VV 254.

Table 9. H I and CO(1–0) Morphological Properties

Source	$L_{\rm FIR}$ (10^{10} L$_\odot$)	No. of Neighbors[a]	Long HI tail[b]	Stretching HI[c]	HI peaks[d] $\neq$ stellar light	CO (1–0) peak[e] $\neq$ galaxy center	Isolated CO (1–0)[f]
VV 55	28.3	12	Y (1.1)	Y	N		
NGC 5257						N	N
NGC 5258						Y (6)	N
VV 48	6.1	23	N (0.9)	N	N		
NGC 5394						N	N
NGC 5395						Y (7)	N
VV 254	7.0	6	N (0.9)	Y	Y		
UGC 12914						Y (8)	Y (9.2)
UGC 12915						N	N
VV 253	32.3	17	Y (2.0)	Y	Y		
NGC 5331N						Y (3)	N
NGC 5331S						N	Y (9.0)
VV 247	14.2	1	Y (1.2)	Y	Y		
NGC 6621						N	Y (9.5)
NGC 6622						···	···
VV 769	4.5	1	N (0.9)	Y	Y		
UGC 813						N	N
UGC 816						N	Y (9.0)
VV 242	7.1	1	N (0.7)	Y	N		
UGC 11984						N	N
UGC 11985						···	···
VV 219	2.2	58	N (0.5)	N	N		
NGC 4567						N	N
NGC 4568						N	N
VV 731	21.5	0	Y (···)	···	Y		
NGC 7592W						N	N
NGC 7592E						N	N
VV 244	2.2	20	Y (1.0)	Y	Y		
NGC 5953						N	N
NGC 5954						N	Y (8.0)

[a]The number of neighboring sources found in Table 2.

[b]A long HI tail is defined when D_{HI}/D_{25} exceeds unity (numbers shown in ()). D_{HI}/D_{25} is the ratio between the major axis of HI and the sum of the 25th isophote of the B-band image from RC3. The HI major axis is estimated from from the lowest column density ($N = 2 \times 10^{20}$ cm^{-2}) contours. D_{HI}/D_{25} is not calculated for VV 731 because of the poor quality of the HI data.

[c]The stretching HI emission is defined when the 10^{21} cm^{-2} column density contours of the pairs appear visually connected.

[d]Identified systems with significant displacement of H I peaks from the stellar disk.

[e]When the location of the CO (1–0) peak column density is not consistent with the center of the galaxy determined from the K-band image to within the CO (1–0) angular resolution. The offsets are shown in () in kpc.

[f]Identified CO (1–0) complexes with no obvious visual evidence of associated optical emission. The masses of the CO (1–0) complexes are shown in () in logarithmic scale of $M_\odot$.

structures to some degree for our program sources.

The simulation analysis in Paper I demonstrates that an emission in the forbidden velocity quadrants of the PVD indicates a radial motion such as gas inflow. There are two cases in this sample in which clear signatures of substantial CO (1–0) emission in the forbidden velocity quadrants are seen: UGC 12915 and NGC 6621. This peculiar emission in UGC 12915 is seen near the center of the galaxy ($\sim 1 - 2$ kpc from the K-band peak), and the associated molecular gas mass is $9 \times 10^8 M_\odot$, which is about 10% of the total molecular gas mass of UGC 12915. A similar feature is seen in NGC 6621, and it is associated with the southeastern CO (1–0) complex about 6 kpc south of the NGC 6621 nucleus. The emission from this complex may belong to the southern tidal arm and to the star forming clusters developing near the overlapping region. If the southern CO (1–0) complex in NGC 6621 is involved in a radial inflow along the tidal arm, this indicates that about 10% of the sources detected in CO (1–0) is showing a possible evidence of inflow, consistent with the predictions made in Paper I.

6.3. Rotation Curves

The rotation curve fitting was performed by tracing the emission envelope of the H I and CO (1–0) PVDs corrected for the instrumental velocity resolution (see Paper I). While the turbulence term removes $\sim$ 10 km s^{-1} from the rotation velocity in normal spiral galaxies, this term is neglected here for consistency since the contribution from turbulent motion in the ISM of colliding systems is unknown. Both sides of the fitted rotation curves are averaged to derive the final rotation curve. Furthermore, to alleviate the discrete velocity sampling and the clumpy nature of the gas emission, each derived rotation velocity is smoothed with a Gaussian whose width is equal to the FWHM of the synthesized beam. Lastly, to avoid oversampling the PVD fit, the number of points were adjusted, typically by a few points per beam, in order to present the points in a smooth and continuous manner. The resultant rotation curves are presented in Figures 16 – 18.

Fig. 6.— Same as Figure 3 but for VV 253.

Fig. 7.— Same as Figure 3 but for VV 247.

Fig. 8.— Same as Figure 3 but for VV 769.

Fig. 9.— Same as Figure 3 but for VV 242.

Fig. 10.— Same as Figure 3 but for VV 219.

Fig. 11.— Same as Figure 3 but for VV 731.

Fig. 12.— Same as Figure 3 but for VV 244.

Fig. 13.— HI and CO (1–0) PVDs. The center of the PVD is chosen to coincide with the 2MASS K-band peak in each galaxy, and the slit is interactively aligned to match the stellar disk major axis. The position angles of the slit are listed in Table 8. The range in the angular offset (x-axis) is significantly different between H I and CO (1–0) because they are different gas tracers. The velocity ranges (y-axis) are similarly different in some cases when the H I and CO (1–0) kinematics are inconsistent.

Fig. 14.— continue from Figure 13. The CO (1–0) PVD for NGC 6622 and UGC 11985 are not available (see text).

Fig. 15.— continue from Figure 14. The H I PVD for NGC 7592 is not available (see text).

The high resolution OVRO CO (1–0) data are used to describe the inner rotation whereas the outer parts of the disk rotation is determined from the lower resolution H I data. Determination of the nuclear gas rotation is limited by the angular resolution of the CO (1–0) observation ($\sim$ 1 kpc), and thus the kinematics of the rising part of the rotation curve cannot be derived with a high accuracy. The rotation curves in the outer parts of the disks are generally flat (within 10 - 20%) with only a few cases showing significant warps (UGC 813/6 and NGC 5257). A smooth transition from the CO (1–0) rotation to H I rotation is seen in 10 of the 15 sources that had robust detection in both H I and CO (1–0). Sources that fail to exhibit smooth and continuous transitions are primarily those with low abundance of the CO (1–0) emitting clouds (e.g. UGC 813/6) although spatial segregation between H I and CO may be important in some cases (e.g. NGC 5394, NGC 5953/4). A high S/N detection of both CO (1–0) and H I results in a well determined rotation curve, and this proves the robustness of our fitting algorithm.

The derived rotation curves can now be used to derive the dynamical mass of each galaxy. The dynamical mass is determined from $M_{dyn} = \frac{R\,V^2}{G}$ where R is the radius of the detected CO (1–0) emission, $V = V_{rot}/\sin i$, where i is the disk inclination, and G is the gravitational constant. Because the disk inclination in interacting systems is exceedingly difficult to determine, we assume $i = 90$ yielding a lower limit in all cases. In addition, M_{dyn} is only computed out to the maximum radial extent of the CO (1–0) emission since the kinematics of the outer disk may be dominated by the tidally perturbed H I gas and may not represent the true rotation of the galaxy. The coarse angular resolution of the H I emission further complicates the exact identification of the diffuse component of the ISM. The results presented in Table 6 show a wide variety of M_{H_2}/M_{dyn} ranging from 0.02 in NGC 5395 to 1.58 in NGC 5394. NGC 5394 is nearly face on and hence the dynamical mass is underestimated substantially (by $\sin^2 i$). For the two edge-on galaxies UGC 12915 and UGC 11984, an inclination correction is not necessary. The M_{H_2}/M_{dyn} ratios of these two systems are 0.18 and 0.14 respectively, and they are consistent with the observed ratios in the inner 500 pc of barred spiral galaxies (Sakamoto et al. 1999). It is important to bear in mind that non-circular motion from the bar can result in an over-estimate of the dynamical mass, but the analysis of numerical simulations suggests that the uncertainty is limited to 30 to 50% (Paper I).

7. Radio Continuum

The 1.4 GHz radio continuum is obtained by combining the line free channels in the H I spectroscopic data. The maps and the total flux are presented in Figure 19 and Table 10 respectively.

Fig. 16.— The fitted rotation curves using HI (*open circles*) and CO (1–0) (*filled circles*) data for VV 55, VV 48, VV 254 and VV 253. Units are arc minutes (*bottom*) and kpc (*top*) for the x-axis and km s^{-1} for the y-axis. The dashed (CO (1–0)) and solid (HI) error bars represent the velocity (y-axis) and spatial (x-axis) resolution.

Natural weighting was used in all images in order to maximize the surface brightness sensitivity. The two galaxies in seven of the systems are clearly resolved, and the total fluxes were derived separately in Table 10. For those that were not completely resolved, the total flux of the two galaxies is given.

Substantial amount of radio continuum in the region between the two galaxies signifies a recent and head-on encounter (Condon et al. 1993; Condon, Helou & Jarrett 2002). Out of the ten systems, only the previously known Taffy systems (VV 254, VV 769) show an obvious radio continuum bridge that connects the two galaxies. The radio continuum peaks in the overlap region between the two galaxies in VV 253, but the poor angular resolution of the data makes it difficult to draw a firm conclusion. Some of the other systems may have also undergone a head-on collision similar to those seen in the Taffy systems, but projection will likely impact the apparent morphology of the radio continuum images. Without the source of energy for re-acceleration of electrons, the radio bridge would quickly fade away, and only the systems that have undergone a collision within the last few tens of million years can be identified in radio continuum.

The SFRs are derived from the radio continuum fluxes for the whole system, and separately for the systems when resolved (Table 10). There are three systems (VV 55, VV 253, VV 731) in which the $SFR_{1.4GHz}$ is noticeably larger than the rest. Even though the radio derived SFR, which indirectly translates to the level of *current* star formation activity, is relatively low compared to those typical of ULIRGs (SFR = 100-1000 $M_\odot$ yr^{-1}), the large amount of molecular gas found in two of these systems (VV 55, VV 253)($\sim 10^{10}$ $M_\odot$) may be enough to initiate and sustain future bursts of star formation. Molecular gas mass is low ($< 10^{10}$ $M_\odot$) in VV 731 despite its relatively high SFR.

8. Individual Sources

In this section, some background information on the individual sources is provided, and a short description of the features seen in the atomic and molecular gas maps and the PVDs are offered.

8.1. VV 55 (NGC 5257/8, UGC 8641, ARP 240)

At a distance of 90 Mpc, VV 55 is one of the more distant sources in the sample of objects presented here. It is classified as a LIRG from its high infrared luminosity ($L_{IR} = 2.8 \times 10^{11}$ $L_\odot$). NGC 5257 is a late type spiral with an inclined "S" optical morphology, where the northern part of the "S" shows a western tidal extension 18 kpc long. The southern tidal feature points eastward and is connected to the northern arm of its companion galaxy, NGC 5258. A low surface brightness

Fig. 17.— Similar to Figure 16 but for VV 247, VV 769, VV 242 and VV 219.

Fig. 18.— Similar to Figure 16 but for VV 731 and VV 244.

Fig. 19.— The distribution of the 1.4 GHz radio continuum emission from all of our program sources. The contours are 1,10,30,50,70,90% of the peak flux.

Table 10. The 1.4 GHz Flux and Star Formation Rates

Source	$S_{1.4\mathrm{GHz}}$ (Jy)	$\mathrm{SFR}_{1.4\mathrm{GHz}}$[a] ($M_{\odot}\ yr^{-1}$)
VV 55		
NGC 5257	0.048	27.8
NGC 5258	0.043	24.9
VV 48		
NGC 5394	0.033	4.2
NGC 5395	0.059	7.4
VV 254		
UGC 12914	0.018	3.9
UGC 12915	0.043	9.3
VV 253	0.044	53.9
VV 247	0.030	14.1
VV 769		
UGC 813	0.018	5.8
UGC 816	0.022	7.1
VV 242		
NGC 7253	0.070	16.2
NGC 7254	0.009	2.1
VV 219		
NGC 4567	0.010	0.6
NGC 4568	0.122	6.8
VV 731	0.075	51.4
VV 244		
NGC 5953	0.074	3.0
NGC 5954	0.021	0.9

[a]Using SFR ($M_{\odot}$ yr^{-1}) = 5.9 × 10^{-22} $L_{1.4\mathrm{GHz}}$ (W Hz^{-1}) (Yun, Reddy & Condon 2001)

diffuse arm 13 kpc long emerges from the southern part of the "S" pointing directly south. Detailed features in the nuclear region of NGC 5257 cannot be seen due to extinction and poor angular resolution of the DSS image, but there is a hint of a dust-lane along the tidal arms. NGC 5258 also shows two tidal features forming a slightly more vertically elongated "S". The southern arm is 40 kpc in length, much longer than the extent of the northern arm. The R-band emission in the nuclear region shows patchy features suggesting obscuration by dust. The Hα emission map shows high levels of star formation activity in the southern arm of NGC 5257, and some activity in the region southwest of the nucleus in NGC 5258, while the nuclei of both galaxies show a low degree of star formation activity (Bushouse & Werner 1990). The far infrared emission at 100 and 160 μm obtained with the Kuiper Airborne Observatory (KAO) shows dust emission emerging from both galaxies (Bushouse, Telesco & Werner 1998).

The H I distribution and kinematics, imaged using the VLA at a $22.2'' \times 17.6''$ (9.8×7.8 kpc) resolution, are shown in Figure 3. The relatively undisturbed distribution of the H I emission in NGC 5257 (Figure 3 (*top*)) suggests that either most of the large scale tidal disturbance occurs along the line of sight, or this particular orbital geometry is less susceptible to the formation of large tidal features (i.e. a retrograde encounter). The diffuse H I emission south of the galaxy shows a small lump that might be associated with the low surface brightness optical tail, in which case the structure may grow to a characteristic H I tail in the future. In contrast, the more face-on galaxy NGC 5258 shows an H I tail 60 kpc long, extending beyond the optical tail traced in the DSS image. This is probably an indication of a prograde encounter. Two peaks separated by 11 kpc can be identified at the northern and southern edge of the disk. The southern peak is spatially coincident with the star forming region found in the 2MASS and Hα images.

The CO (1–0) distribution and kinematics, imaged using the OVRO array at a $6.2'' \times 4.3''$ (2.7×1.6 kpc) resolution, are shown in Figure 3. The CO distribution in NGC 5257 (Figure 3 (*middle*)) shows a concentration near the nucleus with emission extending both in the northeast and southwest forming a 10 kpc long bar. The southern arm shows slightly brighter CO (1–0) emission and is possibly related to the star forming region detected in Hα emission there. The CO (1–0) emission in NGC 5258 (Figure 3 (*bottom*)) forms an elongated "S" shape that closely traces the similar optical morphology. High concentration of CO (1–0) emitting clouds is seen toward the southern portion of the "S", consistent with the elevated level of Hα emission in the same region (Bushouse & Werner 1990). This is one of the few examples in this sample of 10 interacting systems where the CO (1–0) emission traces the tidal arms seen in the optical image. This is a possible indication of an early stage interaction as such a gas morphology is seen during the inflow phase ($t \leq 10^8$ years) in the numerical simulations (Paper I).

The peak intensity in the H I PVD (Figure 13) of NGC 5257 is offset from the center of the galaxy by $4 - 8$ kpc while the CO (1–0) emission in the PVD (Figure 13) is more uniform. The lopsided H I distribution is also evident in the velocity integrated line intensity map (Figure 3 (*top*)), and this is possibly due to higher abundance of CO (1–0) emitting clouds in the warmer and denser conditions near the central region of the galaxy. The derived rotation curve (Figure 16) connects smoothly from CO (1–0) to H I measurements at $V_r \sim 250$ km s^{-1}. The rotation curve declines quickly in velocity ($\Delta v > 100$ km s^{-1}) at large radii (> 15 kpc), indicating that the outer H I disk is strongly warped by tidal stripping of the loosely bound outer disk gas. In NGC 5258, the peak of the H I PVD is lopsided toward the negative offset by 9 kpc while the CO (1–0) PVD is also lopsided but in the opposite direction. The rotation curves derived from these PVDs agree to within 50 km s^{-1}, with a slightly lower velocity for CO. In contrast to the declining velocity seen at large radii in NGC 5257, the H I rotation in NGC 5258 maintains a consistent velocity at 200 - 250 km s^{-1} out to 50 kpc.

8.2. VV 48 (NGC 5394/5, UGC 8898, ARP 84)

VV 48 consists of two late type spiral galaxies, NGC 5394 and NGC 5395, with a projected nuclear separation of 26 kpc. NGC 5394 harbors a strong central starburst (Sharp & Keel 1985; Kaufman et al. 1999) with 10 kpc long tidal arms in both northern and southern directions. NGC 5395 also has multiple tidal arms, with enormous dust lanes dominating the western arm of the galaxy. Extensive star formation activity is seen in Hα emission along the spiral arms forming a large scale elliptical star forming ring (Kaufman et al. 1999). A detailed study of the H I observations using the VLA, a numerical model of the encounter, and BIMA CO (1–0) observations of the northern part of the system are presented in Kaufman et al. (1999) and Kaufman et al. (2002). The BIMA observations had two pointing centers; one toward NGC 5394 and the other toward the northern half of NGC 5395. Kaufman et al. reported that 80% of the CO (1–0) emission in NGC 5394 is found near the central starburst and that NGC 5394 orbit is prograde with respect to the orbital geometry. The "eye-shape" morphology of NGC 5395 prompted them to call this system in a "post-ocular phase".

The H I distribution and kinematics, imaged using the VLA at a $17.8'' \times 16.3''$ (4.0×3.6 kpc) resolution and shown in Figure 4, are the results of our own reduction of the archival data already presented by Kaufman et al. (1999). Multiple H I peaks trace the western dust lane in NGC 5395 while a lower column density gas fills the central and eastern portion of the disk (see Figure 4 (*top*)). Yet fainter H I extension to the north reaches 15 kpc beyond the edge of the stellar disk, and it has a faint optical counterpart in a deep R-band image (Kaufman et al. 1999). One possible explanation to the deficiency of H I in NGC 5394 ($M_{HI} = 7.3 \times 10^8$; Kaufman et al. 1999) is the disk-wide phase transition of atomic to molecular gas. This is evidenced from the large amount of disk molecular gas mass ($M_{\rm H_2} = 3.2 \times 10^9$ M$_\odot$), as well as the strong Hα and radio continuum emission signifying disk-wide star formation activity in NGC 5394 (Kaufman et al. 1999).

The CO (1–0) distribution and kinematics, imaged using the OVRO array at a $5.5'' \times 4.3''$ (1.2×1.0 kpc) resolution, are shown in Figure 4. The new CO data presented here are not only more complete in its coverage but they also represent a three fold improvement in sensitivity and a 20% improvement in resolution over the earlier BIMA observation by Kaufman et al. (2002). Strong CO (1–0) emission is seen in NGC 5394 with a slightly lopsided distribution toward the southwestern side of the galaxy (Figure 4 (*middle*)). The shallow velocity gradient across the CO (1–0) emitting region suggests that the galaxy is nearly face-on. The low column density CO (1–0) extension to the east was not seen in the lower sensitivity BIMA map (Kaufman et al. 2002). The clumpy distribution of CO (1–0) emission in NGC 5395 (see Figure 4 (*bottom*)) roughly traces the star forming ring seen in Hα emission. Each of the four large CO clumps has mass of $M_{H_2} = (0.5 - 1.0) \times 10^9 M_\odot$. The northern CO clump was only marginally detected in the less sensitive BIMA observation, whereas the southern portion of the galaxy was not covered by Kaufman et al. (2002). This is the only galaxy in which CO (1–0) emission is completely absent in the nuclear region among all sample sources detected in CO – a 3σ upper mass limit for the nuclear molecular gas complex is $5 \times 10^6 M_\odot$. The two southwestern CO clumps coincide with the peaks in H I, but the two CO clumps in the eastern half of NGC 5395 have no H I counterparts. The central CO clump, in particular, is detected where the H I emission has a local minimum ($N_{HI} \sim 10^{21}$ cm^{-2}). Because of its clumpy nature, tracing the rotational kinematics in NGC 5395 using the CO (1–0) emission is difficult (Figure 4 (*bottom right*)). Nevertheless, the north-south velocity gradient characteristic of the disk rotation is quite evident. The comparison of the H I and CO mean velocity fields (Figure 4 (*top right*) with Figure 4 (*bottom right*)) suggest that the velocities of the CO emitting clouds are roughly consistent with the velocities of the H I clouds at the same location in the galaxy.

The H I emission in NGC 5394 is very faint, but the H I PVD (Figure 13) clearly shows a disk-like material orbiting the galaxy. A careful comparison with the CO PVD (Figure 13) shows that the velocity gradient is much shallower for the H I, suggesting that the neutral atomic gas lies much farther outside the CO disk, perhaps forming a partial ring or a tidal tail. The CO (1–0) kinematics in NGC 5394 cannot be investigated in detail because of the limited angular resolution. The face-on orientation of the galaxy results in a very low rotational velocity ($V_r \sim 50$ km s^{-1}) in both CO (1–0) and H I (see Figure 16). The H I PVD in NGC 5395 shows peaks near both sides of the tip of the rotation, with a depression of H I toward the galaxy center. The double peak morphology arises from the higher column density H I that is organized in a large scale ring with a diameter $\sim$ 24 kpc. The low abundance of CO emitting clouds in NGC 5395 makes the PVD appear clumpy and discontinuous, but the correspondence to the H I PVD is quite good. The derived CO rotation curve is slightly lower than that of H I (Figure 16), possibly due to the complexity of the fit arising from the clumpy and faint nature of the CO emission.

8.3. VV 254 (UGC 12914/5, Taffy I)

The interacting galaxy pair, VV 254 (hereafter Taffy I), was studied in H I and radio continuum by Condon et al. (1993). They found H I and radio continuum emission connecting the two galaxies whose morphology resembles that of stretching bands of a taffy candy. The long stretched morphology seen in both H I and radio continuum suggests that the collision was strong enough to pull substantial amounts of gas out of the disk, and that the collision was recent enough for the high energy electrons to be still radiating in synchrotron emission. Spectral steepening in the taffy medium constrains the merger age to within $(1-2)\times 10^7$ years of the initial collision (Condon et al. 1993). The collision has also triggered a massive star formation activity in both disks as seen in the near and mid-infrared (Jarrett et al. 1999). More recent studies of the Taffy I include searches for molecular gas in the bridge region. Braine et al. (2003) and Gao, Zhu & Seaquist (2003) have both found $M_{\rm H_2} = 10^9 - 10^{10}{\rm M}_\odot$ of molecular gas in the bridge region, which is comparable to the total molecular gas mass typically found in the disks of nearby spiral galaxies.

The R-band image reveals that UGC 12914 is $\sim$ 16 kpc wide across its major axis, displaying a 6 kpc long tidal arm that extends in the direction of the companion galaxy before eventually curling back. Although fainter, a similar tidal feature is seen near the southern edge of the galaxy, pointing away from its companion. The northern and southern arms form a helical structure reminiscent of the galaxy system commonly known as the "Tadpole Galaxy" (UGC 10214 Tran et al. 2003). UGC 12914 harbors a bright central bulge, with two bright knots located $\sim$ 8 kpc northwest and southeast from the center. The line of sight spatial information is required in order to determine the exact origin of the northwestern knot; it is unclear whether it is associated with the northern edge of the disk or within the tidal arm. At 2μm (Jarrett et al. 1999), the brightest peak is found at the center of the galaxy. The bright optical knots have low surface brightness infrared counterparts. In contrast to the rather unusual optical characteristics seen in UGC 12914, its companion galaxy, UGC 12915, shows morphology and features typical of a colliding late type edge-on galaxy. A strong dust lane encircles the central region of the galaxy, obscuring much of the line of sight optical emission in this region (Bushouse & Werner 1990). In addition, a short, tidally induced warp is seen in the northern edge, possibly connected to the northwestern arm of UGC 12914.

The H I distribution and kinematics, imaged using the VLA at a $18'' \times 18''$ (5.1×5.1 kpc) resolution and shown in Figure 5, are the same data previously published by Condon et al. (1993). The H I emission is widely spread out and extends far beyond the optical disks (Figure 5 (*top*)). The derived total mass of neutral hydrogen is $1.5\times10^{10} M_\odot$, 25% of which (3.8×10^9 M$_\odot$) is found in the bridge region (Condon et al. 1993). The absence of substantial H I emission in both disks may be in part due to absorption against the bright and extended continuum emission. Alternatively, a substantial fraction of H I gas initially distributed in the main body may have already been stripped away to the inter-galactic medium either by ram pressure or tidal force and is now beginning to flow back to the disks.

The CO (1–0) distribution and kinematics are imaged using both natural weighting ($7.2''\times5.1''$ or 2.0×1.4 kpc resolution) and uniform weighting ($4.3'' \times 3.4''$ or 1.2×1.0 kpc resolution), using the OVRO array. The CO (1–0) emission in UGC 12914 coincides with the three optical knots (Figure 5 (see *middle*)). The most massive southern concentration has a mass of $2.4 \times 10^9 M_\odot$ followed by $1.7 \times 10^9 M_\odot$ and $1.6 \times 10^9 M_\odot$ in the central and the northern concentrations. The southern concentration coincides with the peak in H I emission also. Connecting the three molecular complexes is a long and diffuse molecular bridge that spatially coincides with the main dust lane seen in the R-band image. The total molecular gas mass including the diffuse bridge is $8.4\times10^9{\rm M}_\odot$.

An elevated level of Hα emission (Bushouse, private communication) gives compelling evidence of ongoing star formation activity near the vicinity of the three molecular complexes. Since the tidal arm visible in Hα and optical images extends far beyond the OVRO primary beam, it is not possible to identify the presence of any molecular emission in the tidal tails.

In the northern galaxy, UGC 12915, a large amount of molecular gas is found along the large bar-like complex along the projected optical major axis (Figure 5 (*bottom*)). Three resolved CO peaks are identified within the main disk. Two peaks, separated by 5 kpc, occupy the two edges of the CO emission region. The southern peak is brighter of the two. The bar-like ridge at the center is rather complex as it is composed of two spatially distinct peaks separated by less than 1 kpc. A bright Hα association is seen at the outer peaks but the central region is almost devoid of such emission, probably because of heavy obscuration by dust. The peak column density of 4.0×10^{22} cm^{-2} translates to a mean visual extinction of $A_V \sim 80$. This is comparable to that found in NGC 4647 ("The Mice"; $A_V \sim 120$) (Yun & Hibbard 2001), but much smaller than that found in the prototypical ULIRG Arp 220 ($A_V \sim 1000$) (Sakamoto et al. 1999). The estimated molecular gas mass of UGC 12915 is 1.2×10^{10}M$_\odot$.

There is a third major CO emitting cloud in the system, located 5 kpc southwest of UGC 12915, in the bridging region between the two galaxies (Figure 5 (*bottom*)). The deconvolved diameter of this isolated complex is about 2 kpc, and 2.7×10^9 M$_\odot$ of molecular gas (nearly 20% of the molecular gas mass in UGC 12915) is found there. This bridge feature has optical, Hα, and radio counterparts, but it is faint in the K-band light. Earlier BIMA observation with a larger synthesized ($\sim 10''$) beam reported a larger amount (1.4×10^{10} M$_\odot$) of molecular gas in the bridge region (Gao, Zhu & Seaquist 2003). The association with a bright radio continuum peak suggests that the bridge feature is real, and a possible explanation includes a ballistic ejection of molecular clouds from the main body of UGC 12915 during the recent collision. Similar massive ejected CO clouds have also been found in other interacting galaxy systems such as NGC 4676 (Yun & Hibbard 2001).

The H I PVD (Figure 13) morphologies in both sources are quite irregular, probably due to the collision impact that resulted in the ejection of disk H I out to the bridge region. The CO (1–0) PVD (Figure 13) in UGC 12914 is lopsided with strong emission arising from the southern concentration. The resulting CO (1–0) rotation curve is consistent with that of H I at $V_r \sim 300$ km s^{-1} and maintains a constant velocity out to a 30 kpc radius. The high S/N CO (1–0) emission in UGC 12915 results in a well defined PVD that traces the rotation of the disk with distinct emission seen in the forbidden velocity quadrant, signifying inflow (or outflow; see Paper I). The molecular gas mass associated with this kinematically distinct feature is $\sim 10^9$ M$_\odot$, which is less than 10% of the total gas mass of UGC 12915. Similar to its companion, the rotation curve derived from both H I and CO (1–0) are consistent at $V_r \sim 300$ km s^{-1}, but it shows a gradual decline ($\Delta v = 100$ km s^{-1}) at large radii (10 – 30 kpc) probably due to a strong warp in the gas disk (Figure 16).

8.4. VV 253 (NGC 5331, UGC 8774)

VV 253 is one of the brightest (in the IR; $L_{IR} = 3.2 \times 10^{11}$ $L_\odot$) and the most distant galaxy pair in the sample. It consists of two galaxies separated by 18 kpc in the north-south direction, with a low surface brightness dwarf galaxy (NGC 5331W) located 60 kpc west of the galaxy pair. The projected major axis of NGC 5331N is $\sim$ 26 kpc with two arms extending north and south, resembling a reversed $\int$-sign. The southern galaxy, NGC 5331S, is similar in size to NGC 5331N but appears slightly more disturbed than its companion. The southern edge of NGC 5331N and the northern edge of NGC 5331S appear to overlap in the optical image.

The H I distribution and kinematics, imaged using the VLA at a $22.0'' \times 17.1''$ (14×11 kpc) resolution, are shown in Figure 6. The peak H I emission is found in the overlap region with a small lopsidedness toward NGC 5331N (Figure 6 (*top*)). A longer but lower column density extension covers the entire disk of NGC 5331S and beyond. A secondary peak with no optical counterpart is found 26 kpc west of the galaxy pair, and its southwest extension connects to a third low column density peak that coincides with CGCG 017-081. Therefore the observed H I distribution and kinematics suggest an interaction that involves at least three galaxies. The H I emission covers similar velocity ranges in both galaxies in NGC 5331, suggesting that the orbital motion is largely in the sky plane.

The distribution of the CO (1–0) emission, imaged using the OVRO array at a $5.4'' \times 4.4''$ (3.5×2.8 kpc) resolution (Figure 6 (*bottom*)), shows a large amount ($M_{H_2} = 3.0 \times 10^{10} M_\odot$) of molecular gas in the disk of the southern galaxy NGC 5331S. Two molecular arms are attached to the central concentration, and they trace the morphology of the optical tidal arms. The northern galaxy (NGC 5331N) harbors about 10% of the molecular mass of its companion ($M_{H_2} = 3.5 \times 10^9$ $M_\odot$). The peak of the CO (1–0) emission is displaced from the peak of the R-band image to the north by 3-4 kpc. The K-band peak is also similarly offset to the north by about the same amount, thereby suggesting strong extinction along the northern parts of NGC 5331N. Strong extinction toward the nucleus of NGC 5331S is also evident in the R- and the K-band light distribution, but spatial coincidence between the CO and the K-band peaks suggests a high concentration of molecular gas and dust near the nucleus with extended wings along the nearly edge-on disk. The CO velocity field shows a rotation-like gradient in NGC 5331S that is consistent with that of H I, and the peak of the velocity dispersion of both species coinciding with the central CO peak (see Figure 6 (*top right*) and (*bottom right*)).

The H I PVD (Figure 13) in NGC 5331N has an emission peak offset from the center of the galaxy by 15 kpc, which coincides with the global peak of H I emission. The low abundance of CO (1–0) emitting gas in NGC 5331N (Figure 13) makes it difficult to construct a reliable CO rotation curve. Thus only H I emission was used to derive the rotation curve shown in (Figure 16). The H I PVD morphology in NGC 5331S is similar to its companion in that the same global peak is also included within the PVD slit. The CO emission at the center of the galaxy spans the entire velocity range, with a large spread in emission in each velocity channel, resulting in some emission features in the forbidden velocity quadrants. The rotation curve derived from these data show a monotonic decline from $V_r \sim 300$ km s^{-1}to 230 km s^{-1}toward the outer disk at a radius of 23 kpc (see Figure 16). Based on other systems studied here, this decrease in the rotation curve probably indicates a strong warp in the outer gas disk.

8.5. VV 247 (NGC 6621/2, UGC 11175/6, Arp 81)

VV 247 is located at a distance of 81 Mpc with high enough infrared luminosity ($L_{IR} = 1.4 \times 10^{11}$ L$_\odot$) to be classified as a LIRG. It is the fifth system in the Toomre sequence of mergers (see §2) with a projected separation of 17 kpc between NGC 6621 and NGC 6622. NGC 6621 is a late type barred spiral with strong $m = 2$ arms extending to the northwest and southeast, where the northern arm curls around on the northeast side of the system to form a large tidal hook about 75 kpc in projected extent. A large isolated star forming clump is seen in the overlap region 12 kpc southeast of the nucleus of NGC 6621. The disk of NGC 6621 is 21 kpc long in the major axis and 8 kpc in the minor axis, where a long extended dust lane penetrates through the nucleus and toward the southern isolated star forming clump. NGC 6622 is probably an inclined S0 galaxy (Xu et al. 2000) with little sign of tidal disturbance. It is 6 kpc long in the major axis and 4 kpc long in the minor axis. The high resolution HST/WFPC2 image shows a ubiquitous presence of dust lanes in the northern and the southern edges of the galaxy system (Keel & Borne 2003). Numerous star clusters were identified in the disk of NGC 6621, along the long tidal arm, and in the star forming clump in the overlap region (Keel & Borne 2003). Some star forming activity is seen in NGC 6622 as identified by its MIR and Hα distribution (Bushouse & Werner 1990; Xu et al. 2000; Keel & Borne 2003), but at a lower level than in the nucleus of NGC 6621. The star forming region seen in the overlap region also exhibits MIR and Hα enhancement. Strong FIR and 1.4 GHz radio emission are only detected in NGC 6621 (Condon et al. 1996; Bushouse, Telesco & Werner 1998, Figure 19), both showing a southern extension which is possibly related to the isolated southern star forming clump.

The H I distribution and kinematics, imaged using the VLA at a $16.2'' \times 13.0''$ (6.5×5.2 kpc) resolution, are shown in Figure 7. NGC 6621 is one of the few galaxies in our sample whose disk is deficient in H I (NGC 5394 is another example) as well as in the total H I content ($M_{\rm HI} = 4.8 \times 10^9$ M$_\odot$; see Figure 7 (*top*)). The H I emission is centered around the starburst complex in the overlap region, and the absence of CO (1–0) emission there makes this an interesting source for future research using high resolution infrared and optical imaging. The northern part of the tidal tail is also deficient in H I, but a long H I tail exactly tracing a similar optical tail is clearly seen on the northeast side of the system, extending over 20 kpc beyond the optical tail visible in the DSS image.

The CO (1–0) distribution and kinematics, imaged using the OVRO array at a $6.6'' \times 5.6''$ (2.7×2.3 kpc) resolution, are shown in Figure 7. Although faint in H I, NGC 6621 is a bright CO source with a total inferred molecular gas mass of $M_{\rm H_2} = 2.9 \times 10^{10}$ M$_\odot$ (see Figure 7 (*bottom*)). The compact nuclear complex is the dominant CO feature in this system, it accounts for the majority of the CO flux in this system along with the short northwestern extension that traces the dust-lane in NGC 6621 and the longer extension to the southeast with a secondary peak located 6 kpc away. The southeastern extension does not reach far enough to the isolated star forming clump, but it curls northward to form a 5 kpc CO hook that has neither an obvious optical nor H I counterpart. The CO kinematics around the nucleus show the characteristic signature of rotation, but the kinematics toward the southern portion of the galaxy is very complex (Figure 7 (*bottom right*)). No CO (1–0) emission is detected in NGC 6622 with the interferometer despite the reported flux of 34 Jy km $s^{-1}$with the NRAO 12 meter telescope (Zhu et al. 1999). Assuming a linewidth of 410 km s^{-1}(Zhu et al. 1999) our 3σ upper limit CO line flux (6.8 Jy km s^{-1}) in H_2 mass yields 0.5×10^9 $M_\odot$. Their CO (1–0) spectrum shows a possible line detection, but uncertainties in both the baseline fitting and their model approximations are large, and the claimed detection may not be reliable.

The absence of significant H I emission in the disk of NGC 6621 and the high concentration of H I in the overlapping region makes the H I PVD appear completely lopsided (Figure 14). The shape of the CO (1–0) PVD (Figure 14) appears similar to that of NGC 5331S due to the compact nature of the gas and a large range in velocity. The wing toward the negative offset direction arises from the southeastern extension, and this results in a substantial emission in the forbidden velocity quadrant. The H I and CO (1–0) rotation curves of NGC 6621 are consistent at ~ 250 km s^{-1}, but only a limited amount of information is available for the gas poor galaxy NGC 6622 (Figure 17).

8.6. VV 769 (UGC 813/6, Taffy II)

VV 769 is investigated in detail by Bushouse & Werner (1990) in optical/NIR and by Zhu et al. (1999) in CO(1–0) as part of their interacting galaxy surveys. Condon, Helou & Jarrett (2002) identified unusual morphological and radio properties in UGC 813/6 that appear similar to the bridge medium in Taffy I, and thus naming it Taffy II. More recent studies of the Taffy II system include searches for molecular gas in the bridge region. Using the IRAM 30 m telescope, Braine et al. (2004) found $M_{\rm H_2} = 2 \times 10^9$ $M_\odot$ of molecular gas in the bridge region alone, which is comparable to the molecular gas mass found in the bridge region of Taffy I (see §8.3). UGC 813 is nearly edge-on, and the south-eastern edge has a short tidal tail (4 kpc) pointing toward the direction of the southern edge of UGC 816. The western edge of the disk appears less disturbed, but a diffuse tail is visible in high contrast images. UGC 816 appears more face-on than its companion galaxy, and has two tidal arms formed from the recent strong collision with UGC 813.

The H I distribution and kinematics, imaged using the VLA at a $16.3'' \times 16.3''$ (5.7×5.7 kpc) resolution and shown in Figure 8, are the same data previously published by Condon, Helou & Jarrett (2002). The H I distribution has peaks in each galaxy but is offset by a few kpc toward the bridge region (i.e. region between the two disks) in both galaxies (Figure 8 (*top*)). The existence of a long, visible H I tail (~ 20 kpc) in UGC 816 suggests a low inclination disk on a prograde orbit. However, a measurable velocity gradient along the tidal arm suggests a significant inclination along the line of sight. The H I distribution in UGC 813 appears to be less disturbed because its disk has a more inclined projection, but a 10 kpc long tail emanating from the southwest edge of the disk has a lower mean column density. The strong rise in the velocity dispersion in the taffy region signifies the violent nature of the recent collision, similar to that seen in Taffy I.

The CO (1–0) distribution and kinematics, imaged using the OVRO array at a $5.1'' \times 4.1''$ (1.8×1.4 kpc) resolution, are shown in Figure 8. The CO (1–0) emission in UGC 813 (Figure 8 (*middle*)) is distributed along the near edge-on disk, with two marginally resolved peaks separated by 2 kpc. A third peak seen toward the eastern edge of the disk appears to be an extension of the central complex. The peak of the 2MASS K-band image is offset from the CO (1–0) complex, located between the western and the central CO (1–0) complexes. The slight north-south elongation of the larger and more massive northwestern complex results in a slightly lopsided CO (1–0) warp. It is also seen that the CO (1–0) complexes are displaced toward the bridge region, consistent with the H I emission. Its companion, UGC 816 (Figure 8 (*bottom*)), harbors two comparable mass ($M_{H_2} = 1.0 \times 10^9$ $M_\odot$) molecular gas complexes separated by 5 kpc that is further connected by a less massive ($M_{H_2} = 0.5 \times 10^9$ $M_\odot$) molecular bridge. The two large CO (1–0) complexes are displaced by ~ 2 kpc toward the leading edge of the southern spiral arm with the bridge displaced roughly twice as much. Similar to UGC 813 the CO (1–0) displacement is consistent with the H I displacement.

The H I PVDs (Figure 14) in both UGC 813 and UGC 816 have similar characteristics to that of UGC 12914/5. The emission region generally slopes from the upper left to the lower right quadrant, but well defined rotation is absent. This is primarily due to the widely distributed and highly disturbed nature of the H I emitting clouds in this recent collision system. The CO (1–0) PVD (Figure 14) in UGC 813 appears to have significant emission in the forbidden velocity quadrant, but the clumpy nature of the emission makes the determination of the systemic velocity very uncertain. The H I and CO (1–0) rotation curves (Figure 17) in UGC 813 are inconsistent and they differ by ~ 100 km s^{-1}, and the outer disk shows a decline in H I rotation similar to that seen in NGC 5257. The clumpy and asymmetric distribution of CO emission in UGC 816 introduces significant uncertainties in the derivation of the CO rotation curve and results in a significant deviation from the H I rotation curve.

8.7. VV 242 (UGC 11984/5, NGC 7253, ARP 278)

VV 242 is located at a distance of 57 Mpc and consists of two highly inclined galaxies separated by a projected distance of 12 kpc. UGC 11984 is 25 kpc long with the northwestern edge harboring a 9 kpc long low surface brightness, lopsided warp, tilted by 45 degrees from the disk. This is connected to a lower surface brightness (possibly tidal) hook that curls toward the southwestern edge of UGC 11985. The southeastern edge of UGC 11984 appears to overlap with the nucleus of UGC 11985, where a NIR peak and an extended Hα emission is found (Xu et al. 2000). Although slightly shorter, the length of the projected major axis of UGC 11985 is similar to its companion

($\sim$ 20 kpc), also showing similar tidal features in the northwestern edge. Several Hα knots are detected in both disks, with extended NIR and radio continuum emission peaking at the nucleus of UGC 11984 (Condon et al. 1996; Xu et al. 2000). Both disks show evidence of nuclear starbursts where a model fit to the spectra suggest a $1 - 7 \times 10^7$ year time delay in the onset of the nuclear starburst activity (Bernlöhr 1993).

The H I distribution and kinematics, imaged using the VLA at a $17.9'' \times 17.6''$ (5.5×5.4 kpc) resolution, are shown in Figure 9. The H I emission, 46 kpc wide, envelops both galaxies with a depression of H I toward the nucleus of UGC 11984 (see Figure 9 (*top*)). Despite optical evidence of tidally induced tails in the northwestern edge of UGC 11984 pointing south, the morphology of the low column density H I contours shows an extension to the north. The existence of the northern H I extension is puzzling since a general tendency of galaxy collisions is to induce tidal features in the plane of the disk, unless a direct head-on collision results in the collisions of gas clouds at the impact, pulling material out of the plane of the disks, much like the bridge material seen in Taffy I. A similar feature is seen in M82, where the direct "pole-on" passage of M81 caused a strong double warp (Yun 1999). Much of the H I emission in UGC 11985 is confined to the disk with almost all of the northern part attached to the H I in its companion. Since some of the H I emission show physical coupling with the emission in the southeastern edge of UGC 11985, it is likely that the two galaxies are in close physical contact. However, the possibility that the line of sight projection mimics the apparent physical coupling cannot be ruled out.

The CO (1–0) distribution and kinematics, imaged using the OVRO array at a $4.4'' \times 3.1''$ (1.3×0.9 kpc) resolution, are shown in Figure 9. Despite the evidence for nuclear starburst and tidally disrupted H I, the distribution and kinematics of the CO (1–0) emission in UGC 11984 (Figure 9 (*bottom*)) appear to be relatively unaffected by the tidal activity, resembling a normal edge-on spiral galaxy. The peak CO (1–0) emission is found at the nucleus of UGC 11984 with emission extending 11 kpc long along the edge-on disk, where the southeastern side shows longer and narrower emission than the northwestern edge. Its kinematics show a northwest-southeast gradient with a steeper gradient on the northwestern side. The velocity dispersion peaks roughly near the K-band nucleus. No CO (1–0) emission was detected in UGC 11985. Assuming a linewidth of 263 km s^{-1} (Zhu et al. 1999) our 3σ upper limit of H_2 mass in UGC 11985 yields 3.3×10^8 $M_\odot$.

Low abundance of H I emitting clouds near the center of UGC 11984 results in a H I PVD with two distinct peaks (Figure 14), but the higher density tracer in CO (1–0) emission fills the inner region. The CO (1–0) PVD (Figure 14) shows a well defined rotation with the peak slightly offset toward the lower right quadrant. The CO and the H I rotation curves derived from these PVDs are consistent with $V_r \sim 220$ km s^{-1} (Figure 17). The H I PVD in UGC 11985 is similarly lopsided, and the derived rotation curve shows a gradual decline ($\Delta v \sim 50$ km s^{-1}) toward large radii (5 – 10 kpc) – a possible signature for a tidally driven warp.

8.8. VV 219 (NGC 4567/8, UGC 7776/7)

Two early type (Sbc) spiral galaxies constitute the interacting Virgo cluster system VV 219. The absence of any obvious large scale optical tidal features in either system, the proximity of the two disks with projected nuclear separation of $\sim$ 6 kpc, and similar radial velocities (v_{sys} = 2274 (NGC 4567) and 2255 (NGC 4568)) give compelling evidence of a young interacting system. NGC 4567 is a low inclination early-type spiral galaxy (10×5 kpc) with two arms from the northern and southern side of the disk. The northern arm curls toward the northern edge of its companion where dust lanes are visible at the contact region. The southern arm extends in the opposite direction. NGC 4568 is 14×5 kpc in size and its undisturbed appearance resembles a normal early-type spiral galaxy when viewed in the absence of its companion. Numerous dust lanes and strong extended Hα emission are seen throughout the disk, where the most intense emission is found within $r \leq 4$ kpc in NGC 4568 (Koopmann, Kenney & Young 2001). The radio continuum centers around the nucleus of NGC 4568 with an extension toward its companion (Condon et al. (1996), Figure 19).

The H I distribution and kinematics, imaged using the VLA at a $19.9'' \times 14.0''$ (1.6×1.1 kpc) resolution, are shown in Figure 10. The peak H I emission is located on the northern edge of NGC 4568 where the two galaxies appear to overlap (see Figure 10 (*top*)). The emission peaks broadly trace the optical spiral arms while the H I emission has an obvious hole in the central regions of both NGC 4567 and NGC 4568. Such a distribution is commonly seen in nearby spiral galaxies (e.g. Bosma 1981) and is remarkably unexceptional. The extent of the H I disks are comparable to the stellar disks in both galaxies. The outer H I contours show a warp-like feature along the southern tip of NGC 4568, but there is little else that suggests any recent tidal disruptions around either of the galaxies. Because these galaxies reside in a cluster environment, their outer disks are expected to be deficient in H I from repeated ram pressure stripping by the intercluster medium (Cayatte et al. 1990). Any loosely bound tidal material may have also been swept away by the ram pressure stripping. This should occur more intensively near the cluster core as evidenced by the progressively smaller D_{HI}/D_{25} ratio seen among the spiral galaxies toward the core (Cayatte et al. 1994). VV 219 is located at only 650 kpc away in projected distance from the cluster center, and NGC 4567 is one of the H I anemic galaxies found in the cluster.

The CO (1–0) distribution and kinematics, imaged using the OVRO array at a $4.0'' \times 3.5''$ (0.3×0.3 kpc) resolution, are shown in Figure 10. The clumpy CO (1–0) distribution in NGC 4567 is composed of a central molecular complex and the northern and the southern extension that appears to trace optical arms and dust lanes (see Figure 10 (*middle*)). NGC 4568 appears to harbor a central molecular bar a few kpc in extent, connected with two $m = 2$ extension stretching northeast and southwest, together forming a flipped $\int$-sign (see Figure 10 (*bottom*)). At larger scales, molecular gas appears to trace the spiral arms that are the most prominent structures in the outer disk. The "butterfly" shape of the velocity distribution seen in both H I and CO is typically observed in rotationally supported isolated spiral galaxies. Together with the lack of evidence for obvious tidal features in optical and in H I, this may suggest that VV 219 is now commencing its initial collision that marks the epoch $t \sim 0$ in the model analysis in Paper I.

The H I PVD of NGC 4567 (Figure 14) is lopsided toward the lower left quadrant because the H I emission from the northern arm of NGC 4568 is included in the PVD slit. Thus the H I rotation curve at large radii (beyond $\sim 0.7'$) should be neglected. The CO (1–0) PVD of NGC 4567 (Figure 14) is similarly lopsided but at a much smaller scale ($\sim 5''$) than in H I. Overall, the H I and CO rotation curves are consistent in velocity at $\sim$ 80 km s^{-1}, but the H I rotation velocity rises gradually to 120 km s^{-1} in the radius range of 2 – 4 kpc (see Figure 17). The H I PVD in NGC 4568 has two bright emission features both offset by $\sim$ 5 kpc from the center of the galaxy. The central region of the H I PVD is deficient in H I emission, and this is where the CO (1–0) emission dominates. The CO PVD in NGC 4568 peaks along the rising part of the rotation with a slight depression of CO (1–0) near the K-band nucleus, and this may suggest the presence of a nuclear ring. The rotation curves derived from both of these PVDs are relatively well constrained in velocity at $V_r \sim 150$ km s^{-1}.

8.9. VV 731 (NGC 7592, MRK 928)

The optical image of the luminous infrared galaxy, VV 731, suggests that this might possibly be a triplet system. Two large galaxies (NGC 7592E and NGC 7592W) separated by 7 kpc in the east-west direction and a smaller possible companion (NGC 7592S) located directly south of NGC 7592E form the vertices of a small equal lateral triangle. This morphology and the projected separation of 7 kpc between the two nuclei has led to the inclusion of this pair as the 3rd object in the Toomre Sequence of mergers (see §2). NGC 7592W is classified as a Seyfert 2 and NGC 7592E is found to be an H II galaxy (Veron, Goncalves & Veron-Cetty 1997; Rafanelli & Marziani 1992). Two long tidal tails both 15 kpc in projected length emanates from the northern side of NGC 7592W and the southeastern side of NGC 7592E. No MIR emission is detected from the small companion (Hwang et al. 1999). The high resolution HST WFPC2 image (Malkan, Gorjian & Tam 1998) and ground based Hα imaging (Dopita et al. 2002) both suggest that NGC 7592S is a large massive star forming region in the tidal tail of NGC 7592E, similar to what is seen in the southern clump of NGC 6621. The HST/WFPC2 image also reveals that NGC 7592E is more disturbed than its companion, with numerous dust-lanes encircling and penetrating the nuclear region. Rafanelli & Marziani (1992) found a large star formation rate ($\sim 20 M_\odot$ yr^{-1}) from their emission line analysis and the presence of ionized gas at the interface between NGC 7592W and NGC 7592E.

The H I distribution and kinematics, imaged at a $129'' \times 83''$ (36×23 kpc) resolution using the archival VLA data obtained in the D-array in 1983, are shown in Figure 11. The low angular resolution and the poor sensitivity resulting from a short duration of the observations makes a detailed investigation of the emission morphology difficult. In contrast to the other program sources mapped in this study, the peak H I emission is offset from the two galaxies by a large amount ($\sim 2.5' = 71$ kpc; see Figure 11 (*top*)). The exact coincidence of the radio continuum peak with the stellar systems (Figure 19) suggests that the astrometry is correct and the H I displacement real. Such a large offset of H I emission is typically seen in late stage mergers (Hibbard & van Gorkom 1996; Hibbard & Yun 1996). The velocity gradient in the H I tail is in the north-south direction (Figure 11 (*top*)), similar to the sense of rotation implied by the CO (1–0) velocity gradient (Figure 11 (*bottom*)). This may indicate that the long H I tail originates from the disk of NGC 7592W, and future observations with higher resolution and sensitivity will be able to address the H I distribution and kinematics much better.

The CO (1–0) distribution and kinematics, imaged using the OVRO array at a $4.5'' \times 3.6''$ (2.2×1.7 kpc) resolution, are shown in Figure 11. The peak of CO (1–0) emission coincides with the two optical nuclei (see Figure 11 (*bottom*)), each with a nearly identical molecular gas mass of $7\times10^9 M_\odot$. A low column density extension ($M_{H_2} = 7\times10^8$ M$_\odot$) connects the two galaxies, and this discovery is consistent with the detection of ionized gas in the same region (Rafanelli & Marziani 1992). The CO emission in NGC 7592W is elongated from northwest to southeast, but the velocity gradient runs almost perpendicular to it. Such an unusual velocity field is sometimes seen in face-on systems (e.g. NGC 5394 in Fig. 4 (*middle*)). The largest velocity dispersion in NGC 7592W is found near the southeastern part of the galaxy. Along with the unusual velocity gradient, this is evidence for non-circular kinematics caused by the recent interaction. The distribution of CO (1–0) emission in NGC 7592E is elongated east-west with a velocity gradient in the same direction. The molecular gas mass for the CO emission in NGC 7592S ($M_{H_2} = 6 \times 10^8$ M$_\odot$) is about 10% of that detected in NGC 7592E.

The H I PVD is not constructed because of the poor quality of the data. The CO PVDs (Figure 15) for two galaxies display peaks in the lower left quadrants, with secondary peaks near the tip of the rising part of the rotation in the upper right quadrants. Some emission in the forbidden velocity quadrants are detected in both galaxies. Because of the lack of velocity information on larger scales, the CO rotation curves derived from these PVDs offer limited information (Figure 18). The rotation velocity of these two galaxies are comparable at $V_r \sim 200$ km s^{-1}.

8.10. VV 244 (NGC 5953/4, UGC 9903/4, ARP 91)

At a distance of 24 Mpc, VV 244, is one of the nearest galaxy pairs in our sample with a projected nuclear separation of just 6 kpc. NGC 5953 is a face-on spiral 6 kpc across with a large bulge dominating the R-band light distribution. NGC 5953 is classified as a LINER by Veilleux et al. (1995), and as a Seyfert 2 by Gonzalez-Delgado & Perez (1996). A burst of circumnuclear star formation may have been induced by the interaction (Gonzalez-Delgado & Perez 1996). Soft X-ray emission has been detected in NGC 5953, probably related to the Seyfert activity based on the observed variability (Pfefferkorn, Boller & Rafanelli 2001). Its companion, NGC 5954, is 8 kpc long in the projected major axis and 4 kpc long in the minor axis. An optical image shows a southern tail that curls northward forming a small tidal hook. It harbors a LINER nucleus (Gonzalez-Delgado et al. 1997) with no signs of Seyfert activity (Pfefferkorn, Boller & Rafanelli 2001). The HST/WFPC2 F606W imaging by Malkan, Gorjian & Tam (1998) reveals widespread dust lanes and the southern tidal hook in NGC 5953 as well as the numerous dust lanes that occupy the central region in NGC 5954. Interferometric H I observations of VV 244 were previously reported by Chengalur, Salpeter & Terzian (1995), who found a long H I plume extending to the northwest of the pair where only a faint, diffuse optical counterpart is known to exist. They suggested that the plume arises mostly from the tidally ejected gas from NGC 5954, with a small contribution from NGC 5953. From their N-body experiments to model the optical morphology seen in NGC 5954, Jenkins (1984) derived an interaction age of 40 Myr, nearly independent of the orbital parameters.

The H I distribution and kinematics, imaged using the VLA at a $19.8'' \times 17.9''$ (2.3×2.1 kpc) resolution, are shown in Figure 12. The large scale features such as the long H I plume reported by Chengalur, Salpeter & Terzian (1995) are clearly seen. In addition, the superior surface brightness sensitivity of our new data reveal fainter H I features such as the extension to the northeast with a projected distance of ~ 20 kpc from the mean position of the galaxy pair (see Figure 12 (*top*)). A separate H I hook originates from the northwestern side of NGC 5953 extending northward by ~ 6 kpc. It merges with the diffuse emission connected to the northern side of NGC 5954, together forming the long H I plume. The H I emission peaks on both galaxies are systematically shifted toward the faint optical bridge region, as seen in many of the early collision systems studied here.

The CO (1–0) distribution and kinematics, imaged using the OVRO array at a $4.4'' \times 3.6''$ (0.6×0.5 kpc) resolution, are shown in Figure 12. The molecular gas distribution in NGC 5953 is symmetric with a short extension pointing toward NGC 5954 (see Figure 12 (*middle*)). The deconvolved size of the CO emitting region is 1.8×1.4 kpc, and it fills about 20% of the R-band disk. On the other hand, the CO (1–0) emission in NGC 5954 (Figure 12 (*bottom*)) is more densely concentrated near the nucleus with an asymmetric southern extension along the more dominant western stellar arm. The northern and western side of the galaxy are almost devoid of molecular gas. The velocity field in NGC 5953 appears to follow a normal circular rotation where the velocity increases from the northeast to the southwest. The velocity field in NGC 5954 exhibits a north-south gradient, which is consistent with the sense of rotation inferred from the optical morphology.

The H I PVD in NGC 5953 (Figure 15) is significantly lopsided toward the upper left quadrant, with low velocity features covering a larger extent (~ 7 kpc). The CO PVD in NGC 5953 (Figure 15) seemingly traces the rotation well, and the emission peaks are located near the tip of the rotation. The CO rotation curve declines monotonically from $V_r \sim 130$ km s^{-1} to 80 km s^{-1} and does not connect smoothly to that of the H I rotation curve, which has $V_r \sim 150$ km s^{-1} and rises to 200 km s^{-1} at larger radii ($1'' = 7$ kpc). The H I PVD in NGC 5954 is similarly lopsided toward the lower right quadrant, but the CO PVD appears to trace a circular rotation. Similar to NGC 5953, the H I and CO rotation curves do not agree exactly and are offset by $\Delta v = 50$ km s^{-1}(Figure 18), possibly due to tidal stripping of the disk H I gas.

9. Summary and Discussions

Atomic and molecular gases are the dominant constituents of the ISM in galaxies, and tidal perturbations from a companion of comparable mass can significantly alter the distribution and kinematics, leading to compression, inflow, and enhanced star formation activities (e.g. Mihos & Hernquist 1996). As an observational test of such a theoretical scenario, we have identified a sample of 10 pairs of nearly equal mass large disk galaxies in their early stages of interaction or merger and obtained new or archival H I and CO (1–0) data using the VLA and the OVRO millimeter array for the entire sample. The sensitivity and angular resolution of our data are sufficient to allow detailed analysis of H I and CO distribution and kinematics in the complete sample. Some of the key analysis conducted in this work are summarized below.

1. **Atomic and molecular gas masses:** The total neutral atomic gas mass ranges from $1.8 \times 10^9 M_\odot$ to $3.4 \times 10^{10} M_\odot$. The total molecular gas mass derived from the CO luminosity ranges from $7.4 \times 10^8 M_\odot$ to $4.5 \times 10^{10} M_\odot$. More than half of the sources have higher molecular gas mass than atomic gas, and this may suggest the dominance of molecular gas in these colliding galaxies.

2. **Distribution of the H I emission:** H I emission in 50% of the sample sources display long H I tails, indicative of at least one of the galaxies in the pair following a prograde orbit. Four out of five (80%) systems with long H I tails are classified as LIRGs, suggesting a correlation between tidal disruption of outer gas and disk star formation activity. The 10^{21} cm^{-2} column density contours in nearly 80% of the sources are connected between the two galaxies involved in the collision (i.e. Taffy like sources). The environment does not appear to have a significant impact on the development of these large H I tidal features. The H I peaks are offset from the stellar light distribution in six of the groups (VV 244 VV 247, VV 253, VV 254, VV 731, and VV 769; 60%).

3. **Distribution of the CO (1–0) emission:** The CO (1–0) emission peak in four galaxies (NGC 5258, NGC 5331N, NGC 5395, and UGC 12914; i.e. $\sim$ 20%) is offset from the dynamical center of the galaxy determined from the 2MASS K-band images. There are five CO (1–0) emission complexes with no optical counterpart (UGC 12914, UGC 816, NGC 5331S, NGC 5954 and NGC 6621; i.e. $\sim$ 25% of the galaxies).

4. **Position Velocity Diagrams:** More than 50% of the sources in CO (1–0) shows a central hole at the PVD centroid, and this is indicative of an existence of a central gas ring. At least 10% of the sources show substantial CO (1–0) emission in the forbidden velocity quadrant which is a possible evidence of radial inflow (Paper I).

5. **Rotation Curves:** Out of the 15 galaxies with robust derivation of the H I and CO (1–0) rotation curves, five galaxies ($\sim$ 33%; NGC 5395, UGC 813, UGC 816, NGC 5953, NGC 5954) shows significant departure ($\Delta v > 50$ km s^{-1}) between the H I and CO rotation curves. This

may be explained by the fact that molecular gas in general has a clumpy distribution with a lower filling factor than H I, and that the loosely bound disk H I gas is tidally ejected.

The derived physical properties, distribution, and kinematics of the gas were presented in this paper in order to build a statistically significant sample of gas in colliding systems. The characteristics of the physical parameters and the structural parameters can potentially systematically diverge from the same parameters derived for isolated spiral galaxies in the local universe. These analysis using the BIMA SONG data are detailed in Paper III.

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A. Spin Temperature from a Three Cloud Model

The detected H I emission from a narrow velocity channel can be comprised of blended emission from several overlapping clouds with different temperature and density. In order to model the emerging temperature from the blended emission, consider the simple 3 independent thermalized cloud model in Figure 20. Here cloud 1 and cloud 3 have exactly the same properties and they represent the warm neutral medium (WNM) and cloud 2 represents the cold medium (CM) of the ISM. This models a simple H I cloud structure in a disk, and it is motivated by the observed evidence that the scale height of the WNM is about twice as large as that of the CM in the Galaxy. Therefore, assuming a face on galaxy, the emission from the far side of the galaxy (cloud 3) goes through the CM (cloud 2), then through the WNM (cloud 1) and arrives at the observer. The emerging brightness temperature at the observer can be expressed as,

$$T_b = T_1\left(1 - e^{-\tau_1}\right) + \left[T_2\left(1 - e^{-\tau_2}\right) + T_3\left(1 - e^{-\tau_3}\right)e^{-\tau_2}\right]e^{-\tau_1}. \tag{A1}$$

The blended brightness temperature can then be converted to spin temperature assuming $\tau \simeq \tau_1+\tau_2+\tau_3$. The optical depths ($\tau_1 = \tau_3$ and τ_2) are both related to the temperature and density (i.e. $\tau \propto N/T$). Therefore, Equation A1 can be solved easily once an assumption for the density of the clouds are made. Figure 21 shows the results for two cases; $N_1 = N_3 = 0.1N_2$ and $N_1 = N_3 = 0.5N_2$.

The results demonstrated that the temperature of the ISM is of order 100 K at low optical depths ($\tau << 1$) regardless of the cloud densities. When the relative density of the WNM is high (i.e. $N_1 = N_3 = 0.5N_2$), the spin temperature increases more rapidly as a function of τ_2 because the contribution from cloud 1 becomes more significant at higher optical depths. In contrast, when the relative density of the WNM is low (i.e. $N_1 = N_3 = 0.1N_2$), then the dominant contribution arises from cloud 2 regardless of the optical depth, and therefore a shallower slope.

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Fig. 20.— Schematic of the two temperature three cloud model.

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Fig. 21.— Spin temperature as a function of the optical depth of cloud 2. This experiment demonstrates that the spin temperature of the ISM is of order 100 K at low optical depths (i.e. $\tau << 1$).

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