NEW OBSERVATIONS OF EXTRA-DISK MOLECULAR GAS IN INTERACTING GALAXY SYSTEMS, INCLUDING A TWO-COMPONENT SYSTEM IN STEPHAN'S QUINTET

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Received 2000 September 25; accepted 2000 October 31

ABSTRACT
We present new CO (1–0) observations of 11 extragalactic tails and bridges in nine interacting galaxy systems, almost doubling the number of such features with sensitive CO measurements. Eight of these 11 features were undetected in CO to very low CO/H I limits, with the most extreme case being the NGC 7714/5 bridge. This bridge contains luminous H II regions and has a very high H I column density (1.6 × 10^{21} cm^{-2} in the 55" CO beam), yet was undetected in CO to rms \( T_K^{\text{rms}} = 2.4 \) mK. The H I column density is higher than standard H$_2$ and CO self-shielding limits for solar-metallicity gas, suggesting that the gas in this bridge is metal-poor and has an enhanced \( N_{\text{H}_2}/I_{\text{CO}} \) ratio compared with the Galactic value. Only one of the 11 features in our sample was unambiguously detected in CO, a luminous H I–rich star formation region near an optical tail in the compact group Stephan’s Quintet. We detect CO at two widely separated velocities in this feature, at \( \sim 6000 \) and \( \sim 6700 \) km s$^{-1}$. Both of these components have H I and H$_2$ counterparts. These velocities correspond to those of galaxies in the group, suggesting that this gas is material that has been removed from two galaxies in the group. The CO/ H I/H$_2$ ratios for both components are similar to global values for spiral galaxies.

Key words: galaxies: individual (Stephan’s Quintet, NGC 7714, NGC 7715) — galaxies: interactions — galaxies: ISM

1. INTRODUCTION

Large amounts of interstellar gas can be removed from the main disks of spiral galaxies by four main processes: tides due to the gravitational force of a companion, ram pressure stripping during a near head-on collision between gas-rich galaxies, ram pressure stripping by intracluster gas, and galactic winds driven by supernovae. By ejecting processed gas into intergalactic space, these mechanisms contribute to the metal enrichment of the intergalactic medium. In many cases, which of these four processes is active in a given galaxy system can be determined from the optical, radio, and/or X-ray morphology. The signature of a tidal encounter between two galaxies is the presence of long stellar and/or H I tails and bridges (e.g., Toomre & Toomre 1972), while head-on collisions between gas-rich galaxies can produce ring galaxies (e.g., Lynds & Toomre 1976; Theys & Spiegel 1977) as well as gaseous bridges between the galaxies (Struck 1997). Ram pressure stripping by intracluster gas leads to an H I deficiency (e.g., Giovanelli & Haynes 1983), truncation of the outer H I disk of a galaxy (Cayette et al. 1990), and in some cases, bending of the H I disk (Kenney & Koopmann 1999), but not usually removal of large quantities of molecular gas (Kenney & Young 1989). Galactic winds are identified by extended extra-disk ionized gas without stellar counterparts (e.g., Rand, Kulkarni, & Hester 1990).

Star formation sometimes occurs in gas clouds far removed from the main disks of galaxies. Of the four processes that can remove gas from disks, the best-known to trigger the formation of young stars in the stripped gas is tidal forces: numerous examples of luminous H II regions in tidal features have been found (e.g., Schweizer 1978; Mirabel et al. 1991, 1992). Young stars have also been found in extra-disk gas clouds thought to have been stripped during head-on collisions (Smith et al. 1999) and interstellar medium–intracluster medium encounters (Xu, Sulentic, & Tuffs 1999).

In order to better understand the processes that lead to the removal of gas from galaxies and the triggering of star formation in this gas, it is important to make a complete inventory of the gas in these features. This means not just the atomic gas, which has been surveyed in a large number of extragalactic tails and bridges (e.g., Haynes et al. 1984; Smith 1991; Hibbard & van Gorkom 1996), but also the molecular gas. Molecular gas has proved elusive in classical tidal tails; in our earlier CO survey of six tidal tails (Smith & Higdon 1994), no CO was found to very low levels, while only very low mass concentrations of molecular gas (\( \leq 10^7 M_\odot \)) were found in the tidal features of the nearby interacting system M81/M82/NGC 3077 (Brouillet, Henkel, & Baudry 1992; Walter & Heathcote 1999).

In contrast to tidal features, gas removed from galaxy disks by ram pressure during head-on collisions between two gas-rich galaxies may be richer in CO. The prototype of this class of object is the CO-rich gas concentration found outside the disk of the Virgo Cluster galaxy NGC 4438 by Combres et al. (1988). If the standard Galactic \( N_{\text{H}_2}/I_{\text{CO}} \) ratio holds in this feature, it contains \( M_{\text{H}_2} \sim 10^9 M_\odot \). The peculiar morphology of NGC 4438 and the proximity of the companion galaxy NGC 4435 suggests that this clump was removed during a head-on collision between the two galaxies (Kenney et al. 1995). Another apparent example of gas
ram pressure–stripped during a galaxy–galaxy collision is the eastern tail of the peculiar galaxy NGC 2782. This feature has strong CO emission, corresponding to $6 \times 10^8 M_\odot$, assuming the Galactic $N_{\text{H}_2}/I_{\text{CO}}$ conversion factor (Smith et al. 1999). Based on morphological considerations, we surmised that this feature was created during a near head-on collision between two galaxies, rather than a grazing encounter (Smith 1994).

These results suggest that features produced in head-on collisions may differ in a fundamental way from classical tidal tails and bridges formed during grazing encounters: they may be richer in CO. During a head-on collision, the material pulled out into a tail or bridge may originate in the inner disk of one of the galaxies and so may be more metal-rich than gas pulled out from the outer disk in a more distant encounter. The metallicity of the gas may affect the $N_{\text{H}_2}/I_{\text{CO}}$ ratio and therefore the detectability of the CO line. Both theoretical (e.g., Maloney & Black 1988) and observational (e.g., Wilson 1995; Verter & Hodge 1995; Arimoto, Sofue, & Tsujimoto 1996) studies show that low metalicities can lead to enhanced $N_{\text{H}_2}/I_{\text{CO}}$ ratios compared to the Galactic value. In gas with low abundances and dust content, ultraviolet radiation penetrates more deeply into a molecular cloud, causing a larger C$^+$ region relative to the CO core, increasing the $N_{\text{H}_2}/I_{\text{CO}}$ ratio.

The conclusion that tidal gas differs from ram pressure–stripped gas is quite uncertain, in part because of the very small sample size. We have therefore continued our CO survey of extragalactic tails and bridges, selecting systems with high H I column densities, strong star formation rates, and/or ringlike morphologies. In this paper, we present new CO data for tails and bridges in nine additional interacting

### Table 1

| System Name | Galaxies/Tails/Bridges | Optical and H I Morphology |
|-------------|------------------------|---------------------------|
| Arp 144     | NGC 7828               | Ring galaxy$^b$           |
|             | NGC 7829               | Spheroid$^b$              |
|             | H I plume$^c$          | No detected optical counterpart$^d$ |
| NGC 2814/2820 group | NGC 2814               | Sb                         |
|             | NGC 2820               | SB(s)c pec                |
|             | MK 208                 | I0 Pec; near NGC 2814/20 bridge |
| NGC 3395/6  | NGC 3395               | SAB(rs)c pec              |
|             | NGC 3396               | IBm pec                   |
|             | NGC 3395/6 bridge      | Visible in radio continuum$^e$ |
| Arp 105     | NGC 3561A              | SA(s)a Pec                |
|             | NGC 3561B              | S0 Pec                    |
|             | NGC 3561 irregular$^f$ | Connected by stellar bridge to NGC 3561A |
|             | NGC 3561 compact dwarf$^g$ | Immediately south of NGC 3561B |
| Leo triplet | NGC 3627               | SAB(s)b                   |
|             | NGC 3623               | SAB(rs)a                  |
|             | NGC 3628               | Sb Pec                    |
|             | NGC 3628 tail          | Visible in optical and H I maps$^h$ |
| I Zw 192 system | I Zw 192              | Ring or looplike optical structure$^i$ |
|             | I Zw 192 companion     | Compact galaxy connected by bridge$^b$ |
|             | I Zw 192 plume         | Plume extending from companion$^b$ |
| Stephan’s Quintet | NGC 7317             | E4                         |
|             | NGC 7318A              | E2 pec                    |
|             | NGC 7318B              | SB(s)bc pec               |
|             | NGC 7319               | SBB(bc) pec               |
|             | NGC 7320               | SA(s)d; foreground galaxy |
|             | NGC 7320C              | (R)SAB(s)0/a              |
|             | Star formation region A | North of NGC 7318B, near optical tails |
| Taffy galaxies | UGC 12914              | (R)S(r)cd pec             |
|             | UGC 12915              | Sc                        |
|             | UGC 12914/5 bridge     | Visible in radio continuum and H I$^j$ |
| Arp 284     | NGC 7714               | SB(s)b pec                |
|             | NGC 7715               | Im pec                    |
|             | NGC 7714/5 bridge      | H I Offset from optical bridge$^j$ |
|             | NGC 7714 loop          | Visible in optical and H I maps$^j$ |
|             | NGC 7715 tail          | Visible in optical and H I maps$^j$ |

* All information from the NASA Extragalactic Database (NED) unless otherwise noted.

$^a$ Freeman & de Vaucouleurs 1974.

$^b$ Higdon 1988; Fig. 1a.

$^c$ Bosma et al. 1980; van der Hulst & Hummel 1985.

$^d$ Huang et al. 1994.

$^e$ Duc & Mirabel 1994.

$^f$ Kormendy & Bahcall 1974; Rots 1978; Haynes, Giovanelli, & Roberts 1979.

$^g$ Smith 1989; Fig. If.

$^h$ Smith et al. 1993.

$^i$ Smith et al. 1997.
Fig. 1.—Optical images of the nine interacting galaxy systems in our sample, with the locations and FWHM beam sizes of the CO beams marked. All images are from the Digitized Sky Survey (DSS), except when noted. (a) Arp 144 (NGC 7828/9). There is an H I tail without a known optical counterpart to the southeast of the optical pair (Higdon 1988). (b) NGC 2814/20/MK 208. (c) NGC 3395/6. (d) Arp 105 (NGC 3561). This image has been smoothed by a 3'' FWHM Gaussian to enhance low surface brightness features. (e) Brightest galaxy in the Leo Triplet, NGC 3628. A long H I tail extends to the east of NGC 3628 (Rots 1978; Haynes et al. 1979); this tail has a faint optical counterpart not visible in the DSS image shown here (Kormendy & Bahcall 1974). The two marked locations are in this tail. We also observed the center of NGC 3628. (f) I Zw 192. (g) Stephan's Quintet. (h) Narrowband red continuum image of NGC 7714/5 (Arp 284), from Smith et al. (1997). (i) UGC 12914/5 (Taffy galaxies).
We compare these data with the previous results discussed above, as well as the new CO data discussed in Smith (2000), Braine et al. (2000), and Gao et al. (2001).

Throughout this paper, we assume \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. OBSERVATIONS

The CO \((1-0)\) observations were made using the 3 mm SIS receiver on the National Radio Astronomy Observatory (NRAO)\(^1\) 12 m telescope during several observing runs between 1996 and 2000. Two \(256 \times 2\) MHz filter banks, one for each polarization, were used for the observations, providing a total bandpass of 1300 km s\(^{-1}\) with a spectral resolution of 5.2 km s\(^{-1}\). A nutating subreflector with an azimuthal beam throw of 3\(^\circ\) was used, taking care to avoid chopping on other galaxies, tails, or bridges in the system. Each scan was 6 minutes long. The beam size FWHM is 55\(^\prime\) at 115 GHz. The pointing was checked periodically with bright continuum sources and was consistent to 10\(^\prime\). The system temperatures ranged from 200 to 500 K. Calibration was accomplished using an ambient chopper wheel.

A total of 45 positions in nine interacting systems were observed. These nine systems are listed in Table 1, along with a brief description of their optical morphologies. In Figure 1, we display optical images of these systems, obtained from the Digitized Sky Survey\(^2\) (DSS). Table 2 lists the observed positions in the galaxies and tails/bridges; these positions and the CO FWHM beamwidth are marked in Figure 1. Fourteen of the observed positions were in tails or bridges; the rest were in the main disks of the galaxies. A total of 11 tails and bridges were observed. In three systems (Arp 144, NGC 2814/20, and NGC 3628), we observed multiple positions in a single tail or bridge.

Table 2 also lists the central velocities of the observed bandpasses. Note that I Zw 192, NGC 3561B, and position A in Stephan's Quintet were all observed twice, with two different central velocities, to increase the observed bandpass; these two sets of data were combined.

The results of the CO observations are given in Table 3: the line fluxes, velocities, widths, and rms noise levels. The summed spectra for each observed position are displayed in Figure 2. Note that the center of NGC 7828 and one of the tail positions in this system were previously observed by Smith & Higdon (1994); the new and old data have been combined.

\(^1\) The NRAO is a facility of the National Science Foundation, operated under cooperative agreement by the Associated Universities for Research in Astronomy, Inc.

\(^2\) The Digitized Sky Survey was produced at the Space Telescope Science Institute under grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.
### TABLE 2

**CO (1–0) Observations**

| Name                      | R.A. (1950) | Decl. (1950) | Central Velocity (km s⁻¹) |
|---------------------------|-------------|--------------|--------------------------|
| NGC 7828 .................. | 0 3 53.7    | −13 41 40.0  | 5770                     |
| Arp 144 tail No. 1 ........| 0 4 4.2     | −13 43 57.7  | 5700                     |
| Arp 144 tail No. 2 ........| 0 4 10.2    | −13 45 16.0  | 5700                     |
| NGC 2814 .................. | 9 17 9.2    | 64 27 50.0   | 1634                     |
| NGC 2814/20 bridge ....... | 9 17 15.5   | 64 27 23.0   | 1580                     |
| MK 280 .................... | 9 17 26.9   | 64 27 7.0    | 1580                     |
| NGC 2820 .................. | 9 17 43.7   | 64 28 16.0   | 1580                     |
| NGC 2820 NE1 ............. | 9 17 47.0   | 64 28 28.9   | 1580                     |
| NGC 2820 NE2 ............. | 9 17 50.3   | 64 28 41.8   | 1580                     |
| NGC 2820 NE3 ............. | 9 17 53.6   | 64 28 54.6   | 1580                     |
| NGC 2820 NE4 ............. | 9 17 56.9   | 64 29 7.5    | 1580                     |
| NGC 3395 .................. | 10 47 2.7   | 33 14 44.0   | 1620                     |
| NGC 3395/6 bridge .......  | 10 47 6.0   | 33 15 5.8    | 1620                     |
| NGC 3396 .................. | 10 47 8.9   | 33 15 18.0   | 1620                     |
| NGC 3561A ................ | 11 8 31.3   | 28 59 0.9    | 8810                     |
| NGC 3561 irregular ....... | 11 8 31.4   | 29 21 2.1    | 8670                     |
| NGC 3561B ................ | 11 8 31.5   | 28 58 5.5    | 8500, 8700               |
| NGC 3628 .................. | 11 17 40.3  | 13 54 7.0    | 880                      |
| NGC 3628 tail No. 1 ...... | 11 19 46.3  | 13 59 0.0    | 880                      |
| I Zw 192 .................  | 17 39 14.4  | 38 45 21.0   | 12100, 12300             |
| I Zw 192 companion ......  | 17 39 18.4  | 38 46 12.0   | 12300                    |
| I Zw 192 plume ........... | 17 39 19.6  | 38 46 37.0   | 12300                    |
| NGC 7318A ................ | 22 33 39.3  | 33 42 22.2   | 6630                     |
| NGC 7318B ................ | 22 33 40.9  | 33 42 24.1   | 5774                     |
| Stephan's Quintet A ...... | 22 33 41.2  | 33 43 21.5   | 5774, 6630               |
| NGC 7319 .................. | 22 33 46.0  | 33 42 59.4   | 6764                     |
| NGC 7714 west ............ | 23 33 38.9  | 1 52 4.2     | 2800                     |
| NGC 7714 south ........... | 23 33 40.6  | 1 52 1.7     | 2800                     |
| NGC 7714 center ...........| 23 33 40.6  | 1 52 4.2     | 2800                     |
| NGC 7714 north ...........| 23 33 40.6  | 1 53 7.0     | 2800                     |
| NGC 7714 loop ............ | 23 33 40.6  | 1 53 32.0    | 2800                     |
| NGC 7714 east ............ | 23 33 42.3  | 15 24 2.0    | 2800                     |
| NGC 7714/5 bridge ........ | 23 33 44.9  | 15 25 0.0    | 2800                     |
| NGC 7715 center ...........| 23 33 48.3  | 15 24 8.0    | 2800                     |
| NGC 7715 tail ............ | 23 33 51.1  | 15 31 2.0    | 2800                     |
| UGC 12914 SW2 ............ | 23 59 0.4   | 23 11 44.0   | 4371                     |
| UGC 12914 NW2 ............ | 23 59 1.6   | 23 13 17.0   | 4371                     |
| UGC 12914 SW1 ............ | 23 59 2.4   | 23 12 3.0    | 4371                     |
| UGC 12914 NW1 ............ | 23 59 3.0   | 23 12 50.0   | 4371                     |
| UGC 12914 center ......... | 23 59 4.4   | 23 12 22.0   | 4371                     |
| UGC 12914 SE1 ............ | 23 59 5.8   | 23 11 54.0   | 4371                     |
| UGC 12914 bridge .......... | 23 59 6.4   | 23 12 41.0   | 4371                     |
| UGC 12914 SE2 ............ | 23 59 7.2   | 23 11 26.8   | 4371                     |
| UGC 12915 center ..........| 23 59 8.3   | 23 13 0.0    | 4371                     |

**Note.** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

3. **RESULTS**

Out of our nine interacting systems, the only unambiguous detection of CO outside of the main disk of a galaxy is the star formation region in Stephan’s Quintet. In two of our systems (NGC 3395/6 and the Taffy galaxies), the two galaxies in the pair are separated by only 70°–90°, and the star formation regions in the bridges are unresolved from the main disks with our beam size. Thus, although the bridge positions were detected in CO, this may be emission from the galaxy disk in the 12 m beam. Higher resolution follow-up observations are needed to confirm the existence of CO in these regions.

In Table 4, we give the molecular gas mass for the galaxy disks, derived assuming the standard Galactic $N_{\text{H}_2}/I_{\text{CO}}$ ratio [2.8 × 10²⁰ cm⁻²/(K km s⁻¹); Bloemen et al. 1986] and the emission fills the beam ($\eta_c = 0.82$). For the galaxies where more than one position in the disk was detected, the total CO flux from the galaxy was obtained assuming a Gaussian distribution. For the observed extra-disk positions in these systems, the molecular gas mass was derived under the same assumptions and are recorded in Table 5. Although these assumptions may not hold in all cases, they provide a basis for comparison. In Table 5, we also provide the H I column densities averaged over the CO beam, along with the
| Name | $T_R$ (rms)$^a$ (mK) | $I_{CO}^b$ (K km s$^{-1}$) | Line Velocity (km s$^{-1}$) | $\Delta V^c$ (km s$^{-1}$) |
|------|----------------------|--------------------------|-----------------------------|-----------------------------|
| NGC 7828$^d$ | 2.5 | 1.16 ± 0.13 | 5620 | 625 |
| Arp 144 tail No. 1 | 2.5 | ≤0.13$^a$ | 1710 | 260 |
| Arp 144 tail No. 2$^d$ | 2.4 | ≤0.13$^a$ | 1700 | 150 |
| NGC 2814$^e$ | 2.0 | 0.27 ± 0.07 | 360 |
| NGC 2814/20 bridge | 3.6 | ≤0.59$^d$ | 1660 | 420 |
| MK 208 | 3.0 | ≤0.49$^d$ | 8750 | 550 |
| NGC 2820 | 2.4 | 1.19 ± 0.17 | 1600 |
| Arp 144 tail No. 2$^e$ | 2.4 | 0.92 ± 0.18 | 1710 | 260 |
| NGC 2820 NE1 | 2.0 | 0.55 ± 0.14 | 1700 | 150 |
| NGC 2820 NE2 | 2.4 | 1.21$^f$ | 1700 | 150 |
| NGC 2820 NE3 | 2.4 | ≤0.90$^f$ | 1700 | 150 |
| NGC 3395 | 2.5 | 1.19 ± 0.17 | 1600 |
| NGC 3395/6 bridge | 3.6 | 0.92 ± 0.18 | 1660 | 420 |
| NGC 3396 | 5.1 | 0.55 ± 0.14 | 1700 | 150 |
| NGC 3561A | 4.0 | 2.12 ± 0.21 | 8750 | 550 |
| NGC 3561 irregular | 2.3 | ≤0.20$^g$ | 8750 | 550 |
| NGC 3561B | 3.8, 4.3, 2.8 | ≤0.19$^g$ | 8750 | 550 |
| NGC 3628 | 4.8 | 29.58 ± 0.25 | 860 | 400 |
| NGC 3628 tail No. 1 | 2.3 | ≤0.13$^b$ | 12130 | 600 |
| I Zw 192 | 2.5, 1.9, 1.3 | 1.41 ± 0.07 | 12130 | 600 |
| I Zw 192 companion | 2.0 | ≤0.34$^h$ | 12130 | 600 |
| I Zw 192 plume | 3.1 | ≤0.52$^i$ | 12130 | 600 |
| NGC 7318A | 12.7 | ≤2.13$^j$ | 12130 | 600 |
| NGC 7318B | 2.3 | 0.47 ± 0.12 | 6000 | 400 |
| Stephan’s Quintet A | 1.8, 1.7, 1.0 | 0.296 ± 0.059, 0.286 ± 0.048 | 6000 | 140, 180 |
| NGC 7319 | 2.7 | 1.90 ± 0.15 | 6730 | 470 |
| NGC 7714 west | 4.1 | 0.65 ± 0.14 | 2800 | 230 |
| NGC 7714 south | 3.0 | 0.50 ± 0.14 | 2780 | 390 |
| NGC 7714 center | 2.6 | 1.43 ± 0.08 | 2800 | 200 |
| NGC 7714 north | 3.9 | 0.84 ± 0.13 | 2800 | 220 |
| NGC 7714 loop | 4.4 | ≤0.33$^k$ | 2800 | 220 |
| NGC 7714 east | 3.1 | 1.21 ± 0.11 | 2850 | 250 |
| NGC 7714/5 bridge | 2.4 | ≤0.15$^k$ | 2850 | 250 |
| NGC 7715 center | 2.7 | ≤0.21$^k$ | 2850 | 250 |
| NGC 7715 tail | 3.1 | ≤0.16$^k$ | 2850 | 250 |
| UGC 12914 SW2 | 11.4 | ≤1.91$^l$ | 4200 | 620 |
| UGC 12914 NW2 | 13.5 | ≤2.26$^l$ | 4200 | 620 |
| UGC 12914 SW1 | 8.2 | ≤1.37$^l$ | 4200 | 620 |
| UGC 12914 NW1 | 13.1 | 4.89 ± 0.75 | 4200 | 620 |
| UGC 12914 center | 6.1 | 6.50 ± 0.29 | 4330 | 600 |
| UGC 12914 SE1 | 8.2 | 4.10 ± 0.33 | 4550 | 310 |
| UGC 12914 bridge | 8.1 | 12.63 ± 0.53 | 4500 | 830 |
| UGC 12914 SE2 | 9.7 | ≤1.63$^l$ | 4500 | 830 |
| UGC 12915 center | 8.7 | 12.07 ± 0.43 | 4460 | 730 |

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$^a$ As noted in Table 2 and in the text, at three positions two sets of observations were made at two different central velocities in order to increase the observed bandpass. In these cases, the rms values listed correspond to the noise levels for the lower velocity spectrum, the higher velocity spectrum, and the combined overlap region, respectively. Note that for Stephan’s Quintet A, two lines were detected at two different velocities.

$^b$ Statistical uncertainties only.

$^c$ Full width zero maximum (FWZM) line widths.

$^d$ Combined with data from Smith & Higdon 1994.

$^e$ Using $\Delta v = 60$ km s$^{-1}$, from the H$\alpha$ data of Higdon 1988.

$^f$ Using the CO line width of NGC 2820 of 570 km s$^{-1}$.

$^g$ Using the H$\alpha$ line widths of 98 km s$^{-1}$ for NGC 3561B and 161 km s$^{-1}$ for the NGC 3561 dwarf, from Duc et al. 1997.

$^h$ Using the H$\alpha$ line width of 70 km s$^{-1}$ from Rots 1978.

$^i$ Using the CO line width of I Zw 192, 600 km s$^{-1}$.

$^j$ Assuming a line width of 600 km s$^{-1}$.

$^k$ Using the H$\alpha$ line widths of 80 km s$^{-1}$ for NGC 7715, 60 km s$^{-1}$ for the eastern tail of NGC 7715, and 120 km s$^{-1}$ for the northern loop. These widths were obtained from the combined H$\alpha$ data set of Smith & Wallin 1992 and Smith et al. 1997.

$^l$ Using the CO line width of UGC 12914, 600 km s$^{-1}$.
Fig. 2.—Summed CO (1–0) scans for the observed positions, after the spectra have been smoothed by a 36 km s$^{-1}$ boxcar and then resampled at 21 km s$^{-1}$ spacing.
implied $M_\text{H}/M_\text{H}_1$ ratios and the beam size $\Theta$, in kiloparsecs.

For comparison, in Table 6, we give results for 13 other tails, bridges, and extra-disk gas clouds previously observed

### Table 4

**Parameters of the Main Disks of the Sample Galaxies**

| Name           | $M(\text{H}_2)^*$ ($M_\odot$) | $M(\text{H}_2)^*$ ($M_\odot$) |
|----------------|-------------------------------|-------------------------------|
| NGC 7828       | $3.0 \times 10^9$            |                               |
| NGC 2820       | $3.1 \times 10^8$            |                               |
| NGC 2814       | $6.0 \times 10^7$            |                               |
| NGC 3395       | $2.4 \times 10^8$            |                               |
| NGC 3396       | $1.1 \times 10^8$            |                               |
| NGC 3561A      | $1.3 \times 10^{10}$         |                               |
| NGC 3561B      | $\leq 1.2 \times 10^9$       |                               |
| NGC 3628       | $1.6 \times 10^9$            |                               |
| 1 Zw 192       | $1.7 \times 10^{10}$         |                               |
| 1 Zw 192 companion | $\leq 4.1 \times 10^9$     |                               |
| NGC 7318A      | $\leq 7.6 \times 10^9$       |                               |
| NGC 7318B      | $1.7 \times 10^9$            |                               |
| NGC 7319       | $6.7 \times 10^9$            |                               |
| NGC 7714       | $2.2 \times 10^9$            |                               |
| NGC 7715       | $\leq 1.3 \times 10^8$       |                               |
| UGC 12914      | $1.7 \times 10^{10}$         |                               |
| UGC 12915      | $1.9 \times 10^{10}$         |                               |

* Calculated assuming the standard Galactic $N_\text{H}/I_\text{CO}$ ratio ($M_\text{H} = 1.1 \times 10^4$ D$^2$ $\int S_d dV$, where $D$ is the distance in megaparsecs; Bloemen et al. 1986); $H_2 = 75$ km s$^{-1}$ Mpc$^{-1}$, and assuming 34 Jy K$^{-1}$ for the 12 m telescope and the source fills the beam ($\eta = 0.82$). For the two sources with more than one position detected in the disk, the data were fitted to a Gaussian distribution as in Young et al. 1995.

### Table 5

**Parameters of the Extra-Disk Regions**

| Name                | $\Theta$ (kpc) | $M(\text{H}_2)^b$ ($10^8 M_\odot$) | $N(\text{H}_2)^b$ (cm$^{-2}$) | $N(\text{H}_2)^b$ (cm$^{-2}$) | $M(\text{H}_2)/M(\text{H}_1)$ | $L(\text{H}_\alpha)^* / L(\text{CO}) / M(\odot)$ |
|---------------------|----------------|-------------------------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------------------------|
| Arp 144 tail No. 1. | $21$           | $\leq 3.3$                           | $\leq 4.4 \times 10^{19}$     | $9.7 \times 10^{19}$          | $0.91$                         | $L(\text{H}_\alpha)^* / L(\text{CO}) / M(\odot)$ |
| Arp 144 tail No. 2. | $33$           | $\leq 3.3$                           | $\leq 4.4 \times 10^{19}$     | $1.1 \times 10^{20}$          | $0.81$                         |                                               |
| NGC 2814/20 bridge | $5.6$          | $\leq 1.1$                           | $\leq 2.0 \times 10^{20}$     | $\leq 7 \times 10^{20}$       | $\leq 0.20$                    | $\geq 8 \times 10^{25}$                       |
| MK 208             | $5.6$          | $\leq 1.1$                           | $\leq 1.7 \times 10^{20}$     |                               |                               |                                               |
| NGC 3395 bridge    | $5.9$          | $\leq 1.9$                           | $\leq 3.1 \times 10^{20}$     |                               |                               |                                               |
| NGC 3561 irregular | $3.1$          | $\leq 1.2$                           | $\leq 6.8 \times 10^{19}$     | $\leq 7 \times 10^{20}$       | $\leq 0.20$                    | $\geq 8 \times 10^{25}$                       |
| NGC 3628 tail No. 1| $3.2$          | $\leq 0.072$                         | $\leq 4.4 \times 10^{19}$     |                               |                               |                                               |
| NGC 3628 tail No. 2| $3.2$          | $\leq 0.072$                         | $\leq 4.4 \times 10^{19}$     |                               |                               |                                               |
| 1 Zw 192 plume     | $43$           | $\leq 6.2$                           | $\leq 1.8 \times 10^{20}$     |                               |                               |                                               |
| SQ A' 6000 km s$^{-1}$ | $24$          | $1.0 \times 10^{20}$               | $2.5 \times 10^{20}$          | $0.80$                        | $1.2 \times 10^{41}$           | $0.016$                                       |
| SQ A' 7000 km s$^{-1}$ | $24$          | $9.8 \times 10^{19}$               | $2.5 \times 10^{20}$          | $0.78$                        |                               |                                               |
| NGC 7714 loop      | $9.9$          | $\leq 2.1$                           | $\leq 1.1 \times 10^{20}$     | $\leq 9.2 \times 10^{20}$     | $\leq 0.24$                    |                                               |
| NGC 7714 bridge    | $9.9$          | $\leq 0.094$                         | $\leq 5.0 \times 10^{19}$     | $\leq 1.6 \times 10^{21}$     | $\leq 0.63$                    | $1.8 \times 10^{44}$                       |
| NGC 7715 tail      | $9.9$          | $\leq 1.0$                           | $\leq 5.5 \times 10^{19}$     | $\leq 6.5 \times 10^{20}$     | $\leq 0.16$                    |                                               |
| UGC 12914 bridge   | $15$           | $\leq 190$                           | $\leq 4.3 \times 10^{21}$     |                               |                               |                                               |

* All values averaged over the 55" NRAO 12 m beam.

* Calculated assuming the standard Galactic $N_\text{H}/I_\text{CO}$ ratio ($N(\text{H}_2)/I_\text{CO} = 2.8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$) and $M(\text{H}_2) = 1.1 \times 10^4$ D$^2$ $\int S_d dV$, where $D$ is the distance in megaparsecs; Bloemen et al. 1986); $H_2 = 75$ km s$^{-1}$ Mpc$^{-1}$, and assuming 34 Jy K$^{-1}$ for the 12 m telescope and the source fills the beam ($\eta = 0.82$). As noted in the text, these assumptions may not hold for all these sources; they are used for comparison purposes here.

* Not corrected for extinction.

* Because this position is separated from the main disk of the galaxies by less than half of the FWHM beamwidth, the molecular gas mass is given as an upper limit here.

* $H_\alpha$ luminosity from Duc & Mirabel 1994. This was obtained via spectroscopy with a 1.5 slit and so is a lower limit.

* $H_\alpha$ values from Shostak et al. 1984. Both velocity components are included in the $L_{\text{H}_\alpha}/L_{\text{CO}}$ values given here.

* Derived from the data presented in Smith et al. 1997.
Table 6: Parameters of Additional Extra-Disk Regions

| Name                        | Θ (kpc) | \( \frac{M_{\text{H}_2}}{10^4 M_\odot} \) | \( N_{\text{H}_2} \) (cm\(^{-2}\)) | \( N_{\text{H}_1} \) (cm\(^{-2}\)) | \( \frac{M_{\text{H}_1}}{M_{\text{H}_2}} \) | \( L_{\text{H}_\alpha} \) (ergs s\(^{-1}\)) | \( \frac{L_{\text{H}_\alpha}}{M_{\text{H}_2}} \) (L\(_\odot\)/M\(_\odot\)) |
|-----------------------------|---------|--------------------------------------|----------------------------------|----------------------------------|----------------------------------|---------------------------------|----------------------------------|
| Arp 143 tail                | 14      | \( \leq 2.0 \)                       | \( \leq 5 \times 10^{19} \)       | \( 1.1 \times 10^{20} \)         | \( \leq 0.9 \)                    | \( 5.2 \times 10^{39} \)             | 0.009                            |
| Arp 245                     |         | \( 3.5 \)                            | \( 1.5 \)                         | \( 3.6 \times 10^{20} \)         | \( 2.3 \times 10^{21} \)         | \( 0.31 \)                        | \( 1.6 \)                        |
| M81 CO clump                | 0.36    | \( \leq 0.01 \)                      | \( 8 \times 10^{20} \)            | \( 10^{21} \)                     | 1.6                              |                                  |                                  |
| NGC 3077 CO clump           | 0.36    | \( \leq 0.01 \)                      | \( 8 \times 10^{20} \)            | \( 1.5 \times 10^{21} \)         | 1.1                              |                                  |                                  |
| NGC 2782 east tail          | 14*     | \( 6 \)                             | \( 2 \times 10^{20} \)            | \( 6 \times 10^{20} \)           | 0.6                              | \( 4 \times 10^{39} \)             | 0.002                            |
| NGC 2782 west tail          | 14      | \( \leq 1.3 \)                       | \( \leq 8.5 \times 10^{19} \)      | \( 1.1 \times 10^{20} \)         | \( \leq 0.9 \)                    |                                  |                                  |
| NGC 3561 south tail         | 13      | \( 2.3 \)                           | \( 8 \times 10^{20} \)            | \( 2.2 \times 10^{20} \)         | 0.8                              | \( \geq 1.3 \times 10^{40} \)      | \( \geq 0.015 \)                  |
| NGC 4038/9 tail             | 6.1     | \( 0.64 \)                          | \( 1.2 \times 10^{20} \)          | \( 8 \times 10^{20} \)           | 0.3                              | \( 1.7 \times 10^{39} \)             | 0.005                            |
| NGC 4438 CO clump           | 1.8     | \( 8.4 \)                           | \( 2.0 \times 10^{21} \)          | \( 9.2 \times 10^{20} \)         | 5                                | \( \leq 1.6 \times 10^{39} \)      | \( \leq 0.0005 \)                 |
| NGC 4767 north tail         | 23      | \( \leq 6.0 \)                       | \( \leq 5.9 \times 10^{19} \)      | \( 2.1 \times 10^{20} \)         | \( \leq 0.6 \)                    | \( 1.1 \times 10^{40} \)             | \( \geq 0.01 \)                   |
| NGC 7252 north tail         | 17      | \( \leq 2.4 \)                       | \( \leq 4.5 \times 10^{19} \)      | \( 1.8 \times 10^{20} \)         | \( \leq 0.5 \)                    |                                  |                                  |
| NGC 7252 south tail         | 17      | \( \leq 4.5 \)                       | \( \leq 8.5 \times 10^{19} \)      | \( 1.4 \times 10^{20} \)         | \( \leq 1.2 \)                    |                                  |                                  |

* All values averaged over the 55° NRAO 12 m beam except where noted.

Calculated assuming the standard Galactic CO conversion factor. The inferred molecular gas masses for dwarf galaxies in the Sage et al. (1992) sample have Galactic conversion factor applied. For example, the 14\(^{722}\) SMITH & STRUCK Vol. 121

Dwarf galaxies typically have higher \( L_{\text{H}\alpha}/M_{\text{H}_1} \) ratios and lower \( M_{\text{H}_1}/M_{\text{H}_2} \) ratios than normal spirals, if the standard Galactic conversion factor is applied. For example, the 14 dwarf galaxies in the Sage et al. (1992) sample have \( L_{\text{H}\alpha}/M_{\text{H}_2} \geq 0.04 \) \( L_\text{CO}/M_\odot \) and \( M_{\text{H}_1}/M_{\text{H}_2} \leq 0.5 \), after converting to the standard Galactic conversion factor, while all but two of the 25 dwarf galaxies studied by Israel, Tacconi, & Baas (1995) have \( M_{\text{H}_1}/M_{\text{H}_2} \) ratios \( \leq 0.02 \) with this conversion factor. The inferred molecular gas masses for dwarf galaxies may be low because their \( N_{\text{H}_2}/I_{\text{CO}} \) ratio is enhanced due to low metallicities (Maloney & Black 1988). Note, however, that specific locations within dwarf galaxies may have high implied \( M_{\text{H}_1}/M_{\text{H}_2} \) ratios; for example, in IC 10, at positions with \( N_{\text{H}_2} \geq 2 \times 10^{21} \) cm\(^{-2}\), \( M_{\text{H}_2}/M_{\text{H}_1} \sim 3 \) (Ohta, Sasaki, & Saito 1988).

The tails and bridges in Figure 3 that are undetected in

![Diagram](image-url)
CO have upper limits to their $M_{\text{H}_2}/M_{\text{H}_1}$ ratios consistent with global values for dwarfs. The upper limits for the NGC 3561 irregular, the NGC 7714 loop, the NGC 7715 tail, and the NGC 7714/5 bridge are lower than typical global values for spirals; the rest have less strict upper limits.

The subset of these undetected features with Hz fluxes available (NGC 4676, NGC 7714/5, and the northern tail of NGC 3561) have $L_{\text{Hz}}/M_{\text{H}_2}$ lower limits consistent with values for both dwarfs and spirals. However, the Arp 245 feature, the Stephan’s Quintet source, the NGC 4038/9 tail, the eastern NGC 2782 tail, and the NGC 4438 CO clump are brighter in CO relative to Hz than typical dwarf galaxies, while the Stephan’s Quintet feature, the eastern NGC 2782 tail, and the NGC 4438 CO clump have higher inferred $M_{\text{H}_2}/M_{\text{H}_1}$ ratios than dwarfs. The southern NGC 3561 feature has an $M_{\text{H}_2}/M_{\text{H}_1}$ ratio higher than that usually found in dwarfs, but just a lower limit to $L_{\text{Hz}}/M_{\text{H}_2}$.

4. COMMENTS ON INDIVIDUAL GALAXIES

4.1. NGC 7714/5

The most extreme feature in our sample in terms of inferred $M_{\text{H}_2}/M_{\text{H}_1}$ ratio is the bridge of NGC 7714/5. This bridge, which contains luminous H II regions (Arp 1966; Bernlohr 1993; González-Delgado et al. 1995; Smith, Struck, & Pogge 1997), was not detected in CO, in spite of its high column density of atomic hydrogen ($1.6 \times 10^{21}$ cm$^{-2}$ in the CO beam; from the data in Smith et al. 1997). At this bridge, our upper limit implies $N_{\text{H}_2} \leq 5.0 \times 10^{19}$ cm$^{-2}$ and $M_{\text{H}_2}/M_{\text{H}_1} \leq 0.063$, more than 3 times smaller than our upper limit for the system with the second lowest $M_{\text{H}_2}/M_{\text{H}_1}$ ratio in a tail or bridge, the NGC 3561 irregular. The H I column density in this bridge is above the $M_{\text{H}_2}/M_{\text{H}_1}$ CO self-shielding limits for solar metallicity gas ($\approx 5 \times 10^{20}$ cm$^{-2}$ and $10^{21}$ cm$^{-2}$, respectively; Federman, Glassgold, & Kwan 1979; van Dishoeck & Black 1988). However, the nucleus of NGC 7714 is known to be low metallicity (French 1980; Garcia-Vargas et al. 1997), so it is likely that the gas in the bridge would also have low abundances, leading to an enhanced $N_{\text{H}_2}/L_{\text{CO}}$ ratio. Thus there may be more molecular gas in this system than implied by the CO measurements. We note that the mid-infrared camera on the Infrared Space Observatory (ISO) did not detect this bridge (O’Halloran et al. 2000), but it did detect the more distant extra-disk source in Stephan’s Quintet (Xu et al. 1999). This suggests a smaller warm dust component in the NGC 7714/5 bridge.

The smaller galaxy NGC 7715, the eastern tail of NGC 7714, and the H I loop north of NGC 7714 are also weak in CO, with inferred $M_{\text{H}_2}/M_{\text{H}_1}$ ratios $\lesssim 0.16$, $\lesssim 0.16$, and $\lesssim 0.24$, respectively. These may also have enhanced $N_{\text{H}_2}/L_{\text{CO}}$ ratios. Note that NGC 7715, its tail, and the NGC 7714 loop have not been detected in H$\alpha$ (Smith et al. 1997). Also note that NGC 7714 and NGC 7715 have absolute blue magnitudes of $-19.8$ and $-18.1$, respectively (de Vaucouleurs et al. 1991), compared with $-17.7$ for the Large Magellanic Cloud (de Vaucouleurs et al. 1991; Sandage, Bell, & Tripicco 1999). At absolute magnitudes fainter than about $-19$, both irregular and spiral galaxies typically have less than solar metallicities (Skillman, Kennicutt, & Hodge 1989; Vila-Costas & Edmunds 1992; Storchi-Bergmann, Calzetti, & Kinney 1994), thus NGC 7715 may also be metal-poor.

4.2. NGC 2782 and NGC 4438

At the other extreme from the NGC 7714/5 bridge in terms of CO brightness is the eastern tail of NGC 2782 and the extra-disk gas cloud near NGC 4438, with low $L_{\text{Hz}}/M_{\text{H}_2}$ ratios compared to the other features (see Fig. 4). These features have strong CO emission, but little on-going star formation (Combes et al. 1988; Kenney et al. 1995; Smith et al. 1999). None of the features in our new sample are as rich in CO as the NGC 2782 and NGC 4438 features. As discussed at length in Smith et al. (1999), the gas in these features may be metal-rich material removed from the interiors of their disks by near head-on collisions, leading to high CO fluxes. Star formation may be inhibited in these features because of the collision (Smith et al. 1999). Gas clouds pushed out of a galactic disk by a high-velocity collision may compress and then adiabatically expand, reducing their self-gravity. This may decrease the rate of star formation and therefore the $L_{\text{Hz}}/M_{\text{H}_2}$ ratio.

4.3. Arp 245, NGC 3561, and NGC 4038/9

In Figure 3 and Tables 5 and 6, the structure with the highest H I column density in the CO beam is the northern tail of the relatively nearby galaxy Arp 245, which has $N_{\text{H}_1} = 2.3 \times 10^{21}$ cm$^{-2}$ averaged over the 3.5 kpc beam (Duc et al. 2000). As discussed in Duc et al. (2000), this feature is relatively gas-rich and CO-rich ($M_{\text{H}_2} \sim 1.5 \times 10^8$ M$_\odot$, $M_{\text{H}_2}/M_{\text{H}_1} \approx 4.8 \times 10^5$ M$_\odot$, and $M_{\text{H}_2}/M_{\text{H}_1} \sim 0.31$ in the CO beam) and has many properties in common with spiral galaxies. It has an $L_{\text{Hz}}/M_{\text{H}_2}$ ratio similar to spirals, and a stellar population dominated by an underlying old population (Duc et al. 2000). Furthermore, it has a relatively high extinction ($A_B = 2.6$, from the Balmer decrement), a high blue luminosity ($M_B = -17.2$ and $L_B = 1.2 \times 10^9$ L$_\odot$, uncorrected for internal extinction), and a metallicity of $12 + \log(O/H) \sim 8.6$ (Duc et al. 2000). With a modest correction for internal extinction, these values are consistent with the metallicity-luminosity relationship for late-type spirals (Zaritsky, Kennicutt, & Huchra 1994; Garnett et al. 1997). Thus it is possible that this structure may not be a tidal tail, but rather a preexisting edge-on disk galaxy that is interacting with the other two galaxies in the system. High-resolution kinematic data may be useful in testing this hypothesis. In any case, this feature appears to be richer in C$\alpha$ relative to H$\alpha$ and Hz than most dwarf galaxies.

The fact that the Arp 245 feature was detected in CO and many of the other features were not may be due to its high H I column density and relatively high metallicity. There is some evidence that $N_{\text{H}_2}/L_{\text{CO}}$ is correlated with metallicity (Wilson 1995; Verter & Hodge 1995; Arimoto et al. 1996). The trends implied in these papers suggest that at the metallicity of the Arp 245 feature, the $N_{\text{H}_2}/L_{\text{CO}}$ ratio is enhanced only slightly, between 1.5 to 3 times bigger than the Galactic value. Thus, at the high H I column density of the Arp 245 feature, the CO self-shielding limit is exceeded. We note that IC 10, which has a lower oxygen abundance than the Arp 245 feature, shows strong CO at positions where $N_{\text{H}_1}$ exceeds $10^{21}$ cm$^{-2}$ (Ohta, Sasaki, & Saito 1988). At present, the metal abundances of most of the features listed in Tables 5 and 6 are unknown.

The NGC 3561 system (Arp 105; Fig. 1d) contains a spiral (NGC 3561A), an S0 or E galaxy (NGC 3561B), and two tidal features with on-going star formation, presumably pulled out from the spiral galaxy. The concentration of gas...
and star formation in the northern tail is classified as a Magellanic irregular by Duc & Mirabel (1994). The southern feature, which crosses the companion NGC 3561B, is visible as an optical knot in Figure 1d and is classified as a compact dwarf by Duc & Mirabel (1994). This southern feature was detected in CO by Braine et al. (2000), yielding a high $M_{\text{H}_2}/M_{\text{H}}$ ratio in the CO beam of $\sim 0.8$. This ratio is higher than that of the Arp 245 feature, in spite of its more modest H I column density in the CO beam, $\sim 2 \times 10^{20}$ cm$^{-2}$ (Duc et al. 1997) and its lower oxygen abundance $(12 + \log(O/H) \sim 8.4$; Duc & Mirabel 1994). This feature also has a lower blue luminosity ($M_B = -16.9$; $L_B = 9.0 \times 10^8 L_\odot$, uncorrected for internal extinction) and a lower extinction ($A_B = 1.0$) (Duc & Mirabel 1994) than the Arp 245 feature.

The northern tail of NGC 3561 (the Magellanic irregular) has a peak H I column density 4 times higher and a blue luminosity 5 times larger than the southern tail (Duc et al. 1997), and has a higher oxygen abundance $12 + \log(O/H) \sim 8.6$ (Duc & Mirabel 1994), but was undetected in CO, with a lower $M_{\text{H}_2}/M_{\text{H}}$ ratio of $\lesssim 0.2$. The difference between these two tails may be due in part to the difference in beam sizes of our CO observations and the higher resolution observations of Braine et al. (2000), which are less affected by beam dilution. In the interaction scenario for this system presented by Duc et al. (1997), the spiral galaxy NGC 3561A interacts with the elliptical NGC 3561B, drawing out a long tail to the north and a shorter counter-tail to the south. Since both features may have originated in NGC 3561A, it is reasonable to expect they would have similar gas properties. The southern feature may have a relatively small angular size, high column density clump in which the self-shielding limits are exceeded.

If the tentative detection of CO in the NGC 4038/9 tail (Gao et al. 2001) is confirmed by more sensitive observations, it places this tail in the same category as the NGC 3561 and Arp 245 features: it is richer in CO than dwarf galaxies, relative to its Hz flux. The metallicity in this feature has been estimated to be somewhat lower than that in the Arp 245 feature, $12 + \log(O/H) \sim 8.4$ (Mirabel et al. 1992).

4.4. M81 and NGC 3077

The tidal features of M81 and NGC 3077 have also been detected in CO (Brouillet et al. 1992; Walter & Heithausen 1999). Like those in Arp 245 and NGC 3561, they also have high inferred $M_{\text{H}_2}/M_{\text{H}}$ ratios (Table 6). However, the inferred H$_2$ masses in the CO beam are small ($\sim 10^7 M_\odot$, using the standard Galactic $N_{H_2}/I_{CO}$ ratio; $10^7 M_\odot$, using the virial theorem) and there is no evidence for on-going star formation in these locations (Brouillet et al. 1992; Henkel et al. 1993; Walter & Heithausen 1999). The M81/M82/NGC 3077 group is very nearby, so the area subtended by the CO beam ($\sim 360$ pc) is much smaller than in the other systems listed. The other features plotted in Figure 3 have physical beam diameters ranging from 1.8 kpc (NGC 4438) to 43 kpc (I Zw 192). As with the Arp 245 and NGC 3561 features, the CO self-shielding threshold may be exceeded locally in these features. We note that the H I column density in the CO beam is quite high for the M81 and NGC 3077 positions, $10^{21}$ cm$^{-2}$.

A recent larger area CO survey of the NGC 3077 tail (Walters & Heithausen 2001) shows CO in two clumps covering an area of about 3' (2.8 kpc). In this region, the standard Galactic conversion factor gives $M_{\text{H}_2} \sim 6 \times 10^6 M_\odot$ and an average H$_2$ column density of $\sim 8 \times 10^{19}$ cm$^{-2}$. As in IC 10, CO is only detected at H I column densities above $\sim 10^{21}$ cm$^{-2}$. In this larger area, the inferred $M_{\text{H}_2}/M_{\text{H}}$ ratio is smaller, $\sim 0.1$, consistent with the upper limits on the undetected tails and bridges in the sample.

4.5. Stephan’s Quintet

Of the nine extra-disk locations in our new sample, only one was detected in CO: the position in Stephan’s Quintet (HCG 92, Arp 319). Stephan’s Quintet is a compact group of four galaxies with similar velocities ($\sim 6000$ km s$^{-1}$; NGC 7317, NGC 7318A/B, and NGC 7319) and a probable foreground galaxy (NGC 7320) with a much lower velocity ($\sim 800$ km s$^{-1}$). The outlying galaxy NGC 7320C also has a velocity of $\sim 6000$ km s$^{-1}$ and so probably also belongs to this group. Strong gravitational interactions are clearly present in this group (Fig. 1g). A long optical tail stretches more than 1' (26 kpc) to the southeast of NGC 7319; this tail is also detected in H I (Shostak, Sullivan, & Allen 1984; Verdes-Montenegro 2001). Two more optical tails are seen extending to the north of the close pair NGC 7318A/B (see Fig. 1g). Along the easternmost of these features, X-rays (Pietsch et al. 1997) and radio continuum emission (van der Hulst & Rots 1981) are visible, suggesting a shock front. At the location where the two optical tails of NGC 7318A/B intersect, a large concentration of ionized gas has been detected (Moles, Sulentic, & Márquez 1997; Ohyma et al. 1998; Xu et al. 1999). This source is also present in the optical DSS image (Fig. 1g), in the mid-infrared map of Xu et al. (1999), and in H I (Shostak et al. 1984; Verdes-Montenegro 2001). Optical spectroscopy shows that the ionization mechanism for this source is young stars, while spectral signatures of shocks are present to the south, along the radio continuum and X-ray ridge (Moles, Márquez, & Sulentic 1998).

At the location of the extra-disk star formation region in Stephan’s Quintet, we have detected two CO components, at 6000 km s$^{-1}$ and 6700 km s$^{-1}$, at the 5 $\sigma$ and 6 $\sigma$ significance level, respectively. These two components have similar CO fluxes (Table 3). The large velocity separation of these two features argues against the idea that they are caused by the double-horned signature of a rotating disk, but are instead two distinct gas clouds. These two components each contain $1.0 \times 10^9 M_\odot$ of molecular gas, if the standard Galactic $N_{H_2}/I_{CO}$ ratio holds. One of these components (6000 km s$^{-1}$) was detected at a 4 $\sigma$ level in the CO interferometer data of Gao & Xu (2000). We have also detected CO in NGC 7319 and NGC 7318B. NGC 7319 had previously been seen in CO (Verdes-Montenegro et al. 1998; Yun et al. 1997), however, the weaker CO flux from NGC 7318B was not seen in those less sensitive studies. The CO detection in NGC 7318B is at 6000 km s$^{-1}$, a somewhat higher velocity than the optical velocity of this galaxy (5765 km s$^{-1}$; Moles et al. 1998).

Both of the CO components in the extra-disk star formation region have H I counterparts (Shostak et al. 1984). They also both appear to have on-going star formation. Moles et al. (1998) obtained optical spectra of three H II regions in this vicinity; two have velocities of $\sim 6020$ km s$^{-1}$ and one has a velocity of 6680 km s$^{-1}$. Two H z velocity components are also indicated by the narrowband imaging of Xu et al. (1999).

The Hz luminosity, molecular gas mass, and H I mass for
the extra-disk source in Stephan's Quintet are similar to those of many normal spiral galaxies (Young et al. 1996), but unlike those of typical dwarf galaxies (Sage et al. 1992). The implied \( M_{\text{HI}}/M_{\text{H}_2} \) ratios for both velocity components in this region are very high, \( \sim 0.65 \), higher than those typically found for dwarf galaxies (Sage et al. 1992). The \( L_{\text{H}_\alpha}/M_{\text{HI}} \) ratio for the Stephan's Quintet source, 0.016 \( L_\odot/M_\odot \), is consistent with global values for spirals (Young et al. 1996), as well as the values found for the NGC 4676 tail, the Arp 245 feature, and the southern tail of NGC 3561, but is higher than the values seen for the eastern tail of NGC 2782 and the NGC 4438 clump. In Smith et al. (1999), we suggested that star formation was inhibited in the eastern tail of NGC 2782 and the NGC 4438 CO clump because of strong shocks sustained during a head-on collision between two gas-rich galaxies. If the extra-disk cloud in Stephan's Quintet was formed in this way, star formation is clearly not inhibited.

To explain the peculiar morphology of Stephan's Quintet, a number of different interaction scenarios have been suggested. Some of these scenarios involve ram pressure stripping during a head-on collision between two galaxies. For example, Peterson & Shostak (1980) suggest that a head-on collision between NGC 7318B and NGC 7319 removed the gas and caused the radio continuum ridge between them. A different scenario was suggested by Shostak et al. (1984): a prograde tidal encounter of NGC 7320C and NGC 7319 occurred, pulling gas out of these galaxies, creating the long tail south of NGC 7319. This was followed by a high-speed collision between NGC 7318A and NGC 7318B. Other scenarios involve a collision between an "intruder galaxy" (usually NGC 7318B) and intragalactic gas that had previously been tidally stripped or ram pressure-stripped in an earlier encounter between two different galaxies in the group (van der Hulst & Rots 1981; Moles et al. 1997). Moles et al. (1997) suggest that a direct collision between the outlying galaxy NGC 7320C and NGC 7319 occurred in the recent past (10\(^8\) yr ago), removing a large quantity of gas from these galaxies. After this event, NGC 7318B entered the group at high velocity, colliding with this stripped gas and triggering star formation.

Our new data shed some light on the question of the origin of the extra-disk gas in Stephan's Quintet. Our detection of two CO-rich components in the extra-disk star formation region shows that the star formation in this feature was triggered by a collision involving relatively high-metallicity, molecule-rich gas concentrations, rather than metal-poor intracluster medium. This does not rule out ram pressure stripping of NGC 7318B by an intergalactic medium, but it does require that this intergalactic medium be relatively metal-rich gas: gas previously removed from a galaxy. How this gas was originally removed from the disk is unclear: as shown in Arp 245 and NGC 3561, structures apparently created by tidal forces can be relatively CO-rich. Thus this intergalactic gas may have been removed either by tidal forces or via ram pressure stripping.

The 6700 km s\(^{-1}\) extra-disk component may have originally come from NGC 7319 or NGC 7318A, which have similar optical velocities (6650 km s\(^{-1}\) and 6620 km s\(^{-1}\), respectively; Moles et al. 1998). The most likely candidate of these two is the barred spiral NGC 7319, which shows a surprising lack of H II regions (Arp 1973), a long optical tail, and a very offset CO distribution (Yun et al. 1997). NGC 7318A also has an optical tail, however, this may have been created by another interaction.

The 6000 km s\(^{-1}\) extra-disk gas may have originated in either the outlying galaxy NGC 7320C or in NGC 7318B. NGC 7320C has an optical radial velocity of 6000 \( \pm 150 \) km s\(^{-1}\) (Lynds 1972), consistent with this velocity. Previous arguments for the involvement of NGC 7320C (Moles et al. 1997) cited the long tail south of NGC 7319 that points toward NGC 7320C. Alternatively, this component of the extra-disk gas may have come from NGC 7318B. As noted above, our CO observations show a faint CO line in NGC 7318B at this velocity, redshifted 300 km s\(^{-1}\) from the optical velocity. This detection corresponds to a molecular gas mass of \( 1.7 \times 10^9 M_\odot \), assuming the standard \( N_{\text{H}_2}/I_{\text{CO}} \) conversion factor.

We therefore suggest that the extra-disk gas undergoing star formation in Stephan's Quintet originated in NGC 7318B and NGC 7319. At the present time it is unclear whether a single collision between NGC 7318B and NGC 7319 occurred, ram pressure-stripping the gas and creating the shock front between the two galaxies, or whether gas had been removed from NGC 7319 earlier, by an earlier encounter with another galaxy, and then this gas was impacted by NGC 7318B.

5. CONCLUSIONS

We have obtained new CO (1–0) observations of 11 extragalactic tails and bridges, and compared these measurements with previously published data for another 13 features. Of these 24 structures, four have inferred \( M_{\text{HI}}/M_{\text{H}_2} \) upper limits (assuming the Galactic \( N_{\text{H}_2}/I_{\text{CO}} \) conversion factor) less than global values for spiral galaxies, consistent with those found for irregular galaxies. Three of these four CO-poor features are in the NGC 7714/5 system; the most extreme case is the star-forming bridge, which has a very high H I column density (1.6 \( \times 10^{21} \) cm\(^{-2}\) in the 55\(^\circ\) CO beam), yet was undetected in CO, giving an inferred \( M_{\text{HI}}/M_{\text{H}_2} \) upper limit of \( \leq 0.063 \). These features may have enhanced \( N_{\text{H}_2}/I_{\text{CO}} \) ratios compared to the Galactic value due to low metallicities.

Of the 24 structures in our combined sample, eight have been detected in CO. Three of these eight (the Stephan's Quintet extra-disk source, the NGC 4038/9 tail, and the Arp 245 tail) have inferred efficiencies of star formation (\( L_{\text{H}_\alpha}/M_{\text{HI}} \)) consistent with global values for spiral galaxies. In contrast, the \( L_{\text{H}_\alpha}/M_{\text{HI}} \) ratios for the eastern tail of NGC 7282 and the NGC 4438 clump are lower than typical for disk galaxies, suggesting inhibited star formation. In none of the features were our CO limits low enough to conclusively show \( L_{\text{H}_\alpha}/M_{\text{H}_2} \) ratios as high as those found in dwarf galaxies.

Of the eight detected features, two (NGC 2782 and NGC 4438) have optical morphologies indicating head-on collisions. The Stephan's Quintet feature may also have been formed in this manner. In these systems, we suggest that metal-rich gas with an approximately Galactic \( N_{\text{H}_2}/I_{\text{CO}} \) ratio was pulled from the inner parts of the galaxies.

A few recent studies have reported the detection of CO in a number of classical tidal features (e.g., NGC 4038/9, Arp 245, and NGC 3561). In these structures, the H I column density may be locally high enough that the CO self-shielding limit is exceeded, in spite of modestly enhanced \( N_{\text{H}_2}/I_{\text{CO}} \) ratios. There is a slight tendency for these tidal features to have lower \( M_{\text{H}_2}/M_{\text{HI}} \) ratios and higher \( L_{\text{H}_\alpha}/M_{\text{H}_2} \) ratios.
ratios than ram-pressure stripped features discussed above, but there is a large amount of scatter and the sample size is small. More observations are needed to determine whether there is truly a statistical difference in the gaseous and star formation properties of tidal and ram pressure-stripped features.

We are grateful for the help of the NRAO 12 m telescope operators and staff in obtaining these data. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory under contract with NASA. We are pleased to acknowledge partial funding for this project from a NASA grant administrated by the American Astronomical Society and from NSF grant INT-9908542.

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