A Search for CO (1−0) Emission from Tidal Structures near Galaxies

ABSTRACT

We have used the NRAO 12m telescope to search for CO (J = 1 - 0) emission from the tidal tails of seven merging or interacting galaxies. Although these plumes are HI-rich and several are known to contain star forming regions, they are undetected in CO to very low levels. This supports the idea that these structures are material stripped from the outer regions of disk galaxies, where the CO/HI ratio is generally low. The lack of strong CO emission from these plumes in conjunction with the presence of massive star formation is reminiscent of the situation in dwarf irregular galaxies, and is consistent with the hypothesis that dwarf galaxies form from tidal structures.

1. Introduction

The discovery of star forming regions in the tidal tails of interacting galaxies (Schweizer 1978; Mirabel et al. 1991, 1992) provides strong support for the hypothesis that dwarf galaxies form from debris strewn about in intergalactic space by gravitational encounters between galaxies. This theory, which was first suggested by Zwicky (1956), is supported both by detailed models of gravitational clumping in extended tidal features (Barnes and Hernquist 1992; Elmegreen et al. 1993), and by observations of dwarf galaxy-like objects in tidal tails (Schweizer 1978; Mirabel et al. 1991, 1992; Hibbard et al. 1994). Radio observations of tidal features show them to be rich in atomic hydrogen, with numerous clumps of high column density (van der Hulst 1979; Appleton et al. 1987; Higdon 1988; Smith 1991, 1994; Elmegreen et al. 1993; Hibbard 1993, 1994). The HI masses of these clumps (Elmegreen et al. 1993; Hibbard 1994; Smith 1994) are similar to those of dwarf galaxies (Hunter and Gallagher 1985; Kunth 1986), and the star formation rates implied by Hα observations (Mirabel et al. 1991, 1992) are in agreement those of dwarf galaxies, providing support for this dwarf galaxy formation scenario.

The presence of massive star formation associated with these HI clumps suggests that molecular material is also present, especially since the clump column densities often exceed the hydrogen self-shielding limit ($\sim 10^{21}$ cm^{-2}; Federman et al. 1979). While a growing set of optical and radio observations of these tidal features exist, few CO studies have been published. Such information would be useful in determining the nature of the interstellar medium in these structures, as well as in testing this hypothesis of dwarf galaxy formation.

To investigate the molecular content of tidal tails, we have used the National Radio Astronomy Observatory (NRAO) 12m telescope to search for CO (1 - 0) emission from the tidal tails of seven peculiar galaxies or galaxy pairs. These seven systems are tabulated in Table 1. These systems were chosen on the basis of their well developed plumes and the availability of HI data indicating large quantities of atomic gas in the tidal structures. For most of these galaxies, optical imaging data is also available. The seven objects in this sample are all present in the Arp Atlas (1966) of Peculiar Galaxies. Their photographs in the Atlas show long plumes characteristic of recent mergers or close encounters.

In Section II of this paper, we briefly describe the seven systems in the sample. In Section III, we discuss the observations and data, while Section IV we compare the CO properties with tracers of star formation and atomic gas. We discuss our results in Section IV, and summarize our conclusions in Section V.

Throughout this paper, we assume a Hubble constant of 75 km s^{-1} Mpc^{-1}.

2. The Galaxies

2.1. Arp 144 (NGC 7828/9)

Arp 144 is a close pair of galaxies where the northwestern galaxy, NGC 7828, is a disturbed disk galaxy with optical plumes and a ring-like structure, and

NGC 7879 is an spheroidal system with peculiar low surface brightness extended features (Arp 1966). An HI map of this system (Higdon 1988) shows a maximum at NGC 7828, and a gigantic HI structure extending $\sim$130 kpc to the southeast, with an HI mass of 3×10^9 $M_\odot$. No optical counterpart to this HI feature is seen on the Palomar Observatory Sky Survey (POSS) plates. At present, no optical imaging data of this galaxy pair is available.

This galaxy system has been suggested as an example of a collision between a spiral galaxy and an intergalactic HI cloud (Freeman and deVaucouleurs 1974). In this model, the HI from the disk galaxy is removed during the collision, creating a gaseous ring in which star formation is induced. The HI data for this galaxy is consistent both with this hypothesis and with a scenario in which Arp 144 is an ongoing merger of two galaxies (Higdon 1988).

2.2. Arp 143 (NGC 2444/5)

Arp 143 is an elliptical/ring galaxy pair (Arp 1966). The ring galaxy NGC 2445 contains very blue knots of young stars (Burbidge and Burbidge 1959; Appleton, Schombert, and Robson 1992) which lie on the outer edge of an HI intensity enhancement (Appleton et al. 1992). This arrangement is predicted by models of density wave induced star formation in ring galaxies (Appleton and Struck-Marcell 1987; Struck-Marcell and Appleton 1987), and supports the view that the ring structure was formed by a head-on collision between the two galaxies, as in the ring formation models of Theys and Spiegel (1977) and Toomre (1978).

The elliptical companion NGC 2444 lies $30''$ northwest of NGC 2445. Near this location, a 200 kpc long HI tail joins the system, extending to the northwest (Appleton et al. 1987a, b). The origin of this feature is uncertain; it may be stripped gas from NGC 2444, a tidal tail, or gas removed by a collision (Appleton et al. 1987a).

2.3. Arp 215 (NGC 2782)

Arp 215 is a relatively isolated galaxy with a long HI tail on one side of the galaxy (Smith 1991, 1994), and a bright optical plume on the other side (POSS plates; Arp 1966). No HI is seen at the tip of the stellar plume, however, low optical surface brightness emission is present in the HI tail (Smith 1991). Unsharp masking of optical imaging data reveals three ripple-like structures in the disk of NGC 2782; these ripples have optical colors similar to that of the underlying disk (Smith 1994). Bright Hα emission is seen at the nucleus and along the northwestern section of the inner ripple (Hodge and Kennicutt 1983; Smith 1994). No optical imaging data is available as yet for the long HI tail. CO (1-0) observations of the disk of this galaxy indicate a large amount of molecular gas is present; using the standard Galactic CO/H_2 ratio (Bloemen et al. 1986), $M(H_2)$ = [ ] $M_\odot$ (...) within the inner [ ]$'$.

The ripples in this galaxy may be due to a head-on collision between two unequal mass disk galaxies, where the disrupted smaller galaxy has become the stellar plume, and the long HI tail is material pulled out from the outer disk of the larger galaxy by tidal forces (Smith 1994). Alternatively, this galaxy may be a merger remnant, where the ripples are distorted spiral patterns or due to expanding shock fronts due to winds from the nuclear starburst (Smith 1994).

2.4. Arp 244 (NGC 4038/9)

The famous Antennae galaxy Arp 244 is well-studied at many wavelengths. This system is clearly two galaxies in the process of merging; it has two long thin optical tails, and two distinct galactic disks which are in contact (Arp 1966). Radio mapping of this system has revealed HI counterparts to the optical tails; approximately 70% of the atomic gas in the system is associated with these tails (van der Hulst 1979; Mahoney, van der Hulst, and Burke 1994). Star forming regions have been discovered at the tip of the southern tail (Schweizer 1978);

these have HI and optical properties similar to those of dwarf galaxies (Mirabel, Dottori, and Lutz 1992). Optical spectroscopy of these HII regions indicate low metallicity (Mirabel, Dottori, and Lutz 1992).

Within the central regions of NGC 4038/9, the H_2 mass is 2.6×10^9 $M_\odot$ (Sanders and Mirabel 1985), determined from CO (1-0) measurements and a standard conversion factor. Interferometric observations show CO peaks at the two galactic nuclei and at the region of overlap of the two disks (Stanford et al. 1990).

2.5. Arp 242 (NGC 4676)

Like the Antennae, the Mice have two prominent tidal tails and two distinct disks (Arp 1966). In the case of the Mice, the two galaxies are connected by a bridge (Arp 1966). Large amounts of atomic gas are present in these tails, and Hα mapping reveals HII regions along the tails (Hibbard et al. 1993). This pair is well-modeled by a gravitational encounter between two equal mass disk galaxies (Toomre and Toomre 1972).

2.6. Arp 102

Arp 102 consists of a disturbed spiral galaxy (UGC...) with a long optical plume extending to the north, connected by a bridge to a relatively distant elliptical in the south (Arp 1966). HI mapping (Higdon 1994) shows [ ]. This system is likely the result of a strong gravitational encounter between the two galaxies.

2.7. Arp 226 (NGC 7252)

Arp 226, popularly known as the 'Atoms for Peace' galaxy, has a single main body with two long optical tails and arcs and loops surrounding the main galaxy (Arp 1966). This galaxy appears to be a late-stage merger remnant; the optical surface brightness radial profile fits an $R^{1/4}$ law, indicating that the stellar distribution has relaxed to resemble that of elliptical galaxies (Schweizer 1982).

The morphology of this galaxy has been well-reproduced by a merger model (Borne and Richstone 1991; Mihos et al. 1993).

The HI in this system is nearly all associated with the tidal tails and loops; the main galaxy is void of atomic gas (Hibbard et al. 1994). In contrast, large amounts of CO emission have been detected from the central region (Dupraz et al. 1990). HII regions have been detected at the tips of the tails with properties similar to those of dwarf galaxies (Hibbard et al. 1994).

3. ^{12}CO (J = 1 − 0) Observations

Observations of the plumes in the ^{12}CO (J = 1 − 0) line (115.2712 GHz) were made using the 3 mm SIS receiver on the NRAO 12m telescope[1] on Kitt Peak, Arizona, during 1994 February 9-12. Two 256 × 2 MHz filterbanks, one for each polarization, were used for these observations, providing a total bandpass of 1300 km s^{-1} and a spectral resolution of 5.2 km s^{-1}. Calibration was accomplished using an ambient chopper wheel. Most of the observations were made using a nuating subreflector with a beam throw of $2'-3'$. In some cases, position switching was necessary to avoid chopping onto the target galaxy or onto the plume; in those cases, the reference beam was located $4'-6'$ away in azimuth. At this frequency, the beamsize is FWHM = $55''$. The pointing was checked periodically with bright continuum sources, and was found to be consistent to $\sim10''$, except in one instance (marked in the table), where a shift of $25''$ was noted. The system temperatures ranged from 200K to 450K. Each 6 minute scan was checked individually for baseline problems, and was not used if there were obvious deviations which affected the summed spectrum. A linear baseline was fitted and removed from the summed spectra.

The observed positions in the plumes are listed in Table 1. For the 4 galaxies without published CO measurements for the main galaxy, we also obtained CO data for the main body of the galaxy in addition to data for the plumes. These locations are given in Table 2. The final summed CO spectra for the positions in the plumes are shown in Figure 1. As can be seen in Figure 1, we did not detect emission from any of the plumes. In Table 1, we record the rms noise level $T_A{}^*$ reached in these observations, along with the central velocity of the observed bandpass.

We detected emission from three out of the four galaxies observed in the central regions. In Table 2, along with the rms noise level, we have recorded the integrated CO flux density $I(CO) = \int T_R dV$, calculated assuming the CO in the plume fills the beam (efficiency $\eta = 0.5$). In Arp 144A we detected CO at the location of the HI maximum, centered at NGC 7828. We made an 9 position half-beamwidth spacing map of Arp 143, and found an asymmetric CO distribution, skewed to the northwest. We detected CO at the locations of both galaxies in the Mice, Arp 242. No CO was seen towards Arp 102A. In Figure 3, we display the spectra for Arp 144A, Arp 242A and B, and Arp 102A. The data for Arp 143 is presented in plot format and discussed in more detail in a separate publication (Higdon et al. 1994).

REFERENCES

Appleton, P. N., and Struck-Marcell, C. 1987, ApJ, 318, 103.

Appleton, P. N., Ghigo, F. D., van Gorkom, J. H., Schombert, J. M., and Struck-Marcell, C. 1987a, Nature, 330, 140.

Appleton, P. N., Ghigo, F. D., van Gorkom, J. H., Schombert, J. M., and Struck-Marcell, C. 1987b, Nature, 330, 500.

Appleton, P. N., Schombert, J. M., and Robson, E. I. 1992, ApJ, 385, 491.

Arp, H. C. 1966, Atlas of Peculiar Galaxies, (Pasadena: California Institute of Technology).

Barnes, J., and Hernquist, L. 1992, Nature, 360, 715.

Bloemen, J. B. G. M., et al. 1986, A&A, 154, 25.

Borne, K. D., and Richstone, D. O. 1991, ApJ, 369, 111.

Burbidge, E. M., and Burbidge, G. R. 1959, ApJ, 130, 12.

Combes, F. in Star Forming Dwarf Galaxies and Related Objects, eds. D. Kunth, T. X. Thuan, and J. Tran Thanh Van (Singapore: Kim Hup Lee Printing Co.), 307.

Dupraz, C., Casoli, F., Combes, F., and Kazes, I. 1990, A&A, 228, L5.

Elmegreen, B. G., Kaufman, M., and Thomasson, M. 1993, submitted to ApJ.

Federman, S. R., Glassgold, A. E., and Kwan, J. 1979, ApJ, 227, 466.

Freeman, K. C., and de Vaucouleurs, G. 1974, ApJ, 194, 569.

Hibbard, J. E., van Gorkom, J., Westpfahl, D., and Kasow, S. 1992, in The Evolution of Galaxies and their Environment, Third Teton Summer School.

Hibbard, J. E., Guhathakurta, P., van Gorkom, J. H., and Schweizer, F. 1994, AJ, in press.

Higdon, J. L. 1988, ApJ, 326, 146.

Hunter, D., and Gallagher, J. 1985, ApJ Sup, 58, 533.

Kunth, D. 1986, in Star Forming Dwarf Galaxies and Related Objects, eds. D. Kunth, T. X. Thuan, and J. Tran Thanh Van (Singapore: Kim Hup Lee Printing Co.), 183.

Mahoney, J. H., van der Hulst, J. M., and Burke, B. F. 1993, in preparation.

Mihos, J. C., Bothun, G. D., and Richstone, D. O. 1993, ApJ, in press.

Mirabel, I. F., Lutz, D., and Maza, J. 1991, A&A, 243, 367.

Mirabel, I. F., Dottori, H., and Lutz, D. 1992, A&A, 256, L19.

Schweizer, F. 1978, Structure and Properties of Nearby Galaxies, ed. E. M. Berkhuijsen and R. Wielebinski, 279.

Schweizer, F. 1982, ApJ, 252, 455.

Smith, B. J. 1991, ApJ, 378, 39.

Smith, B. J. 1994, AJ, in press.

Stanford, S. A., Sargent, A. I., Sanders, D. B., and Scoville, N. Z. 1990, ApJ, 349, 492.

Tacconi, L. J., and Young, J. S. 1987, ApJ, 322, 681.

Theys, J. C., and Spiegel, E. A. 1977, ApJ, 212, 616.

Toomre, A., and Toomre, J. 1972, ApJ, 178, 623.

van der Hulst, J. M. 1979, A&A, 71, 131.

Toomre, A. 1978, IAU Symposium 79, The Large Scale Structure of the Universe, ed. M. S. Longair and J. Einasto (Dordrecht: Reidel), p. 109.

Toomre, A., and Toomre, J. 1972, ApJ, 178, 623.

Zwicky, F. 1956, Ergeb. Exakt. Naturwiss., 29, 344.