Atomic and Molecular Gas in Ring Galaxies

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We present a survey of the ^{12}CO(1–0) and HI emission of a sample of 16 collisional ring galaxies (see Horellou et al. (1995a) for more details). We have found that ring galaxies are bright in CO compared to normal galaxies. Their mean HI content, however, is not significantly different. If the standard conversion factor from CO emissivities into H_2 column densities holds for ring galaxies, this indicates that a large amount of molecular gas is available for star formation and that ring galaxies are currently actively forming stars. This result is in agreement with their high far-infrared luminosities. The Cartwheel, often considered as the prototype of ring galaxies, has not been detected. We suggest that the weak CO emission of this galaxy is due to its low metallicity.

HEAD-ON COLLISION OF TWO GALAXIES

Ring galaxies are believed to form when a compact galaxy plunges through the center of a rotating disk system. The galaxy in transit exerts a brief inward pull on the stars of the target galaxy, which execute radial harmonic oscillations in addition to their initial circular motion. A series of ring waves forms and propagates through the target disk, as numerical simulations have convincingly demonstrated (e.g., Lynds & Toomre 1976; Theys & Spiegel 1977). These radially expanding waves are accompanied by a strong burst of star formation: observed ring galaxies are usually very blue and possess large HII regions (Theys & Spiegel 1976; Jeske 1986). Their average far-infrared luminosity L_{FIR}, far-infrared to blue luminosity ratio L_{FIR}/L_B and color temperature $T(60\mu\text{m}/\ 100\mu\text{m})$ are also significantly greater than those of normal galaxies (Appleton & Struck-Marcell, 1987). Ring galaxies thus provide an example of coherent starbursts on a scale often larger than 10 kpc.

The interstellar medium of ring galaxies is poorly known. Although true ring galaxies are not very numerous, no systematic study of their atomic and molecular gas properties has been undertaken. This may be because many rings have small angular sizes so that they can hardly be resolved by single-dish telescopes either at centimeter or millimeter wavelengths. On the other hand, they are often too faint to be detectable with interferometers. The work presented here is a first step towards a better knowledge of the atomic and molecular gas content in these peculiar objects.

THE OBSERVATIONS

- 16 ring galaxies observed in the ^{12}CO(1–0) line with the SEST and 30m IRAM telescope
- 6 galaxies observed in HI with the Nançay, Parkes and Arecibo radiotelescopes. HI data were available in the literature for 6 more objects

See list in Table 1. Eleven out of the 16 ring galaxies have been taken from the list of Appleton & Struck-Marcell (1987). The sample contains nearby galaxies such as AM1045–245 at a velocity of 3730 km s^{-1} as well as very distant objects such as the Sextans ring at 16500 km s^{-1}. We have observed well-studied objects such as the Cartwheel and the Vela ring, but also galaxies of which almost nothing is known (e.g., IRAS20210+1121). Four galaxies of the sample (NGC985, Sextans, IRAS20210 and AM1045-245) host a Seyfert nucleus. Out of the 16 objects, one was not detected by IRAS both at 60 and 100 μm (IIHz4) and one (IIZw28) was detected at 60 μm only.

Table 1. The Sample

Name	v_{hel} km s^{-1}	Size ($''$,$''$)	B_T^o	S_{60} Jy	S_{100} Jy
IC4448	4580	60x48	13.2	2.32	5.02
AM064-741 (=Lindsay-Shapley ring)	6611	95x50	13.0	1.42	4.2
AM0530-421	14500	60x60	13.8	0.55	1.86
Vela	4845	70x50	12.8	1.06	3.65
Cartwheel	8934	74x60	13.9	0.65	1.6
AM1045-245	3730	132x120	12.7	2.38	3.94
NGC985	12948	39x23	13.9	1.44	2.0
Sextans	16500	19x17	15.5	0.92	1.5
Arp147	9655	19x16	15.7	0.98	1.9
IIZw28	8611	14x10	14.9	<0.5	<1.00
IRAS20210	16900		15.8	3.31	2.78
Arp119	14265	78x36	14.2	0.73	1.65
IIHz4	12830	29x32	15.6	<0.5	<1.00
Arp143	4020	85x70	13.6	3.39	6.32
Arp148	10350	22x15	15.1	6.06	10.66
Arp145	5178	58x40	13.6	0.83	1.83

Table 2. Luminosities and Masses

Name	$D^{(a)}$ Mpc	L_{FIR} $10^{10}L_\odot$	L_B $10^{10}L_\odot$	M(HI) $10^9M_\odot$	Reference $HI^{(b)}$	$M(H_2)$ $10^9M_\odot$	$L_{FIR}/M(H_2)$ $L_\odot/M_\odot$
IC4448	61	2.27	2.91	4.4	(7)	1.7	13.3
AM064-741 (=Lindsay-Shapley ring)	88	3.73	7.77			3.2	11.6
AM0530-421	193	7.9	17.2	46.0	(7)	5.2	12.4
Vela	65	1.76	5.11	0.7	(1)	1.42	12.4
Cartwheel	119	2.66	6.31	33.0	(2)	<1.50	>17.8
AM1045-245	50	1.34	3.32	4.6	(7)	0.47	28.5
NGC985	173	9.02	12.9	<5.8	(3)	12.0	7.5
Sextans	220	11.1	4.75	18.0	(7)	11.5	9.6
Arp147	129	3.99	1.36	5.2	(4)	2.2	18.1
IIZw28	115	<1.65	2.17	2.3	(4)	<0.85	
IRAS20210	225	34.4	3.68			4.1	83.9
Arp119	190	7.15	11.8	12.0	(7)	4.05	17.6
IIHz4	171	<3.65	2.62	8.3	(4)	1.3	>28.1
Arp143	54	2.36	1.65	6.6	(6)	3.00	7.9
Arp148	138	26.7	2.83			11.5	23.2
Arp145	69	1.05	2.67	1.4	(7)	2.3	4.6

a) Distance to the galaxy (H=75 km s^{-1} Mpc^{-1})

b) References: 1) Martin, private communication; 2) Mebold et al. 1977; 3) Heckman et al. 1978; 4) Jeske 1986; 5) Giovanelli et al. 1981; 6) Gallagher et al. 1981; 7) this work.

GLOBAL RESULTS

Out of the 16 ring galaxies that we have observed, we have detected 14 in the ^{12}CO(1–0) transition. HI masses are known for 12 ring galaxies. Table 2 gives an overview of the results.

- *Gas content*

To compare observed quantities from one galaxy to another, we need to scale them to the mass or size of the object. Since the diameters at the 25th mag arcsec^{-2} isophote, D_{25}, of these disturbed objects are not well determined (and unknown in many cases) we have chosen to scale all quantities and in particular the gas masses to the blue luminosity L_B.

To compare the gas content of ring galaxies with that of normal galaxies, we have used the distance-limited sample of 66 nearby galaxies observed in CO by Sage (1993a,b).

The atomic hydrogen content of ring galaxies is very comparable to that of the control sample (see Table 3). **Ring galaxies are neither HI-rich nor HI-deficient**. On the other hand, **they are CO bright** and H_2 rich compared to the control sample. Their H_2 content is more than twice as high as for the control sample galaxies. The two samples are statistically different in their mean far-infrared and blue luminosities.

- *Star formation activity*

Few observational data related to star formation are available for ring galaxies. The only parameters that exist for the whole sample are the far-infrared fluxes obtained by IRAS. The far-infrared luminosity of a galaxy is partly due to the reemission by dust grains of the UV emission of massive stars; it can be therefore be used as an indicator of the recent star formation activity. Meanwhile, this is clearly not the best measure since dust heated by the interstellar radiation field as well as active nuclei also contribute to the far-infrared emission.

The far-infrared luminosities and the far-infrared to blue luminosity ratio $L_{FIR}/L_B$are higher for ring galaxies. Not surprisingly, we found that the far-infrared luminosities correlate with the H_2 masses. All the quantities are normalized since they have been divided by L_B. The correlation is better with the molecular gas mass alone than with the total gas mass content (HI+ H_2)/L_B. This result has been found by several authors for larger samples (e.g., Young et al. 1989). This suggests that the molecular gas rather than the atomic gas is linked to star formation, at least as it is revealed by the far-infrared emission.

The star formation efficiency as measured by the ratio of the far-infrared luminosity and the molecular gas mass L_{FIR}/M(H_2) is higher for ring galaxies than for galaxies of the control sample (Table 2). Of course, it would be of great interest to compare other indicators of star formation such as the UV emission, the Hα emission or the radiocontinuum emission with each other and with the CO and FIR emission. Unfortunately, such data are not available for ring galaxies yet.

Table 3. L_{FIR}/L_B values and normalized HI and H_2 masses

	log[LFIR/LB]	log[M(HI)/LB]	log[M(H2)/LB]
S93	-0.73±0.37=log(0.19)	-0.72 ± 0.56= log(0.19)	-1.58 ± 0.45= log(0.026)
Rings	0.01±0.47=log(1.02)	-0.83 ± 0.47= log(0.15)	-1.18 ± 0.41= log(0.066)

TWO INDIVIDUAL CASES

- **Cartwheel**

The Cartwheel is a spectacular southern ring galaxy. It consists of a large and very blue outer ring (diameter of 34 kpc) with bright HII regions connected to a yellow inner ring by spokes. The galaxy has experienced a recent burst of star formation. It has a high far-infrared luminosity and (60 μm /100 μm) color temperature (2.6 10^{10} $L_{\odot}$and 33.3 K respectively). It is also rich in atomic gas (M(HI)= 10^{10} $M_{\odot}$, Mebold et al. 1977). Color gradients have been observed throughout the disk, the bluer stars being located at larger radii (Marcum et al. 1992); this is in agreement with the idea of a density wave propagating outwards through the disk.

We have observed the Cartwheel in the CO(J=1-0) line during several observing sessions at SEST. Because of the large angular size of the galaxy (more than 80" along the major axis) we have made a 5-point map with 45" sampling. We also observed the positions at offsets (-29" -7.7") and (-7.7" -29") which correspond to bright knots in the optical picture. **None of these positions was detected.** The total integration time on the galaxy is 34 hours (2033 minutes!) and the r.m.s. noise in 30 km s^{-1}channels 0.6 mK. The upper limit on the H_2 mass is then 1.5 10^9 $M_{\odot}$ if we take the HI linewidth (355 km s^{-1}, Mebold et al. 1977) and assume that the emission is extended on about 80 arcsec scale. This would in turn imply that the galaxy contains **at least 20 times more atomic hydrogen than molecular hydrogen**. Of all the sample galaxies for which the HI mass is known, the Cartwheel would have the lowest H_2/HI ratio.

Despite its prominent star formation activity the CO emission of the Cartwheel is very low. This does not mean that it does not contain any molecular hydrogen. Indeed, the Cartwheel is found to be very deficient in heavy elements (Fosbury & Hawarden 1977): oxygen, nitrogen, and neon are lower by factors of 6, 22, and 3 when compared to the Orion nebula (in the Large Magellanic Cloud oxygen is deficient by a factor 2 only and CO emission is weaker by a factor of 6, Cohen et al. 1988). The Cartwheel may thus be undergoing one of its first epoch of star formation and its progenitor galaxy could be a gas-rich low-surface-brightness galaxy, as suggested by Marcum et al. (1992). Indeed, there is no evidence of old stars in the outer ring. The non-detection of CO emission could then be due to the low amount of CO molecules **because of the low metallicity** and not to the absence of molecular gas. However, the limit on the H_2 mass is not very good (this is due to the large distance and angular size of the Cartwheel). The value of $L_{FIR}/\mathrm{M(H_2)}$ is not especially high ($>$ 17.7) and the value of $\mathrm{M(H_2)}/L_B$ ($<$ 0.024) not especially low. Both are within the range where most galaxies are found (Horellou et al. 1995b). It is thus difficult to reach definite conclusions concerning the molecular hydrogen content of the Cartwheel and this disappointing case testifies to the actual limitations of CO observations.

- **Vela**

The Vela ring is a distinctive object among ring galaxies, mainly because of its central bar which makes it resemble the greek letter θ. Vela's morphology is complex : there are *three rings* with major axis diameters of 73"= 23 kpc, 17"= 5.4 kpc and 10"=3.2 kpc respectively, *and two bars*, one connecting the outer ring to the inner ring structures and the second connecting the inner ring to the nucleus. Vela's kinematics are complicated as well: the outer ring has an expansion velocity of 39 km s^{-1} and almost no rotation (v_{rot}= 13 km s^{-1}); the inner ring has about the same rotational velocity (v_{rot} = 15 km s^{-1}, Taylor & Atherton 1984, Hα). This implies an extremely low dynamical mass: about 10^9 $M_{\odot}$.

We have mapped Vela in the CO(1-0) and CO(2-1) transitions and detected signals only at the center position. **The lines are extremely narrow: 35 $\pm$ 6 and 28 $\pm$ 5 km^{-1}** respectively (from a gaussian fit), which is very unusual for a galaxy nucleus. Even most galaxies seen almost face-on have linewidths of about 100 km s^{-1}. Those linewidths agree however with the Hα ones. The HI line is narrow as well (less than 100 km s^{-1}, Dennefeld & Martin 1995).

The total molecular gas mass that we derive is twice as high as the HI mass (M(H_2)= 1.4 10^9 $M_{\odot}$;

$M(HI) = 7\ 10^8\ M_\odot$). Our 22" CO(2-1) beamwidth covers the inner 7 kpc (D=65 Mpc). Assuming that the CO lines are thermalized ($I_{21} \approx I_{10}$), one can derive an H_2 mass of $4\ 10^8\ M_\odot$ within that region, which is of the same order of the dynamical mass estimated by Taylor and Atherton inside the inner ring radius. This is rather unusual but the uncertainties in both the molecular and the dynamical masses are large (because of the use of the 2–1 transition and of the low inclination of the galaxy respectively). Nevertheless, **a large fraction of the mass in the central regions of Vela is in molecular form**, a characteristic which is often seen in mergers. The narrowness of the line and the low dynamical mass probably indicate that the gas is concentrated in the very central part of the galaxy and/or that Vela is far from dynamical equilibrium.

References

Appleton P.N., Struck-Marcell C., 1987, ApJ 312, 566
Cohen R.S. et al., 1988, ApJ 331, L95
Dennefeld, M., Martin, J-M, 1995 in prep (A&A)
Fosbury, R.A.E., Hawarden, T.G., 1977, MNRAS 178, 473
Gallagher, J.S., Knapp, G.R., Faber, S.M., 1981, AJ 96 1781
Giovanelli, R., Chincarini, G.L., Haynes, M., 1981, ApJ 247, 383
Heckman, T.M., Balick, B., Sullivan, W.T., 1978, ApJ 224, 745
Horellou C., Casoli F., Combes, F., Dupraz C., 1995a, A&A 298, 767
Horellou C., Casoli F., Dupraz C., 1995b, A&A, in press (Fornax galaxies)
Jeske N., 1986, PhD thesis, University of Berkeley, California
Lynds, R., Toomre, A., 1976, ApJ 209, 382
Marcum, P.M., Appleton, P.N., Higdon, J.L., 1992, ApJ 399, 57
Mebold, U., Goss, W.M., Fosbury, R.A.E., 1977, MNRAS 180, 11P
Sage, L.J., 1993a, A&A 272, 123
Sage, L.J., 1993b, A&ASS 100, 537
Taylor, K., Atherton, P. D., 1984, MNRAS 208, 601
Theys, J.C., Spiegel, E.A., 1976, ApJ 208, 650
Theys, J.C., Spiegel, E.A., 1977, ApJ 212, 616
Young, J.S., Xie, S., Kenney, J.D.P., Rice, W.L., 1989, ApJ Suppl. Series 70, 699