Bekki, K., Koribalski, B. S., Ryder, S. D., Couch, W. J. (2005). Massive H i clouds with no optical counterparts as high-density regions of intragroup H i rings and arcs.

Originally published in *Monthly Notices of the Royal Astronomical Society: Letters, 357*(1), L21–L25.
Available from: http://dx.doi.org/10.1111/j.1745-3933.2005.08625.x

Mon. Not. R. Astron. Soc. **000**, 1–?? (2004) Printed 2 February 2008 (MN LaTeX style file v1.4)

Massive HI clouds with no optical counterparts as high-density regions of intragroup HI rings and arcs

K. Bekki[1], B. S. Koribalski[2], S. D. Ryder[3], and W. J. Couch[1]
[1] *School of Physics, University of New South Wales, Sydney 2052, NSW, Australia*
[2] *Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping NSW 1710, Australia*
[3] *Anglo-Australian Observatory, P.O. Box 296, Epping NSW 1710, Australia*

Accepted, Received, in original form June 2004

ABSTRACT

We present a new scenario in which massive intragroup HI clouds are the high-density parts of large HI rings/arcs formed by dynamical interaction between galaxy groups and gas-rich, low surface brightness (LSB) galaxies with extended gas disks. Our hydrodynamical simulations demonstrate that the group tidal field is very efficient at stripping the outer HI gas of the disk if the gaseous disk of the LSB galaxy extends $2-5$ times further than the stellar disk. We find that a massive, extended 'leading stream' orbiting the group's center can form out of the stripped outer HI envelope, while the severely shrunk LSB galaxy, whose stellar disk remains unaffected, continues on its path. The result is a relatively isolated, massive HI cloud with a ring- or arc-like shape, a very inhomogeneous density distribution ($N_{\rm HI} \sim 1.0 \times 10^{17} - 1.1 \times 10^{20}$ atoms cm^{-2}), and, initially, no stellar content. Only the high density peaks of the simulated intragroup HI ring/arc can be detected in many current HI observations. These will appear as relatively isolated 'HI islands' near the group center. We also find that star formation can occur within the ring/arc, if the total gas mass within the intragroup ring/arc is very large ($\sim 4 \times 10^9$ M$_\odot$). We discuss these results in terms of existing observations of intragroup gas (e.g., the Leo Ring and HIPASS J0731–69) and intergalactic HII regions.

Key words: ISM: clouds – intergalactic medium – radio lines: ISM – galaxies: interaction.

1 INTRODUCTION

Massive intragroup HI gas clouds with apparently no optical counterparts are known to exist in several galaxy systems (for overviews see, e.g., Hibbard et al. 2001, Koribalski 2004). While many of these clouds are clearly part of tidal streams/bridges formed by and still connected to interacting or merging galaxies, like for example the Magellanic Clouds (Putman et al. 2003), the M 81 group (Yun et al. 1994), the NGC 3256 group (English et al. 2004), and IC 2554 (Koribalski et al. 2003), only a few are found at relatively large distances from their apparent progenitors. The most spectacular example in the latter category is the massive, intergalactic HI gas cloud, HIPASS J0731–69 ($v_{\rm hel} \approx 1480$ km s^{-1}), in the NGC 2442 galaxy group (Ryder et al. 2001). This extended cloud, which has an HI mass of $\sim 10^9 M_\odot$ and lies at a projected separation of 180 kpc from the gas-rich, asymmetric spiral galaxy NGC 2442*, was discovered in the HIPASS Bright Galaxy Catalog (Koribalski et al. 2004) and is the only definite extragalactic HI cloud in this catalog.

Surrounding the elliptical galaxy NGC 1490, Oosterloo et al. (2004) found several intragroup HI clouds with a total HI mass of $\sim 10^{10}$ $M_\odot$ distributed along an arc 500 kpc long. Large clumpy HI rings (diameter $\sim$ 200 kpc) have also been detected around the E/S0 galaxies M 105 ('The Leo Ring', Schneider et al. 1989), NGC 5291 (Malphrus et al. 1997; Duc & Mirabel 1998) and NGC 1533 (Ryan-Weber et al. 2003). These are in contrast to the much smaller, smooth HI rings (diameter $\sim$ 25 kpc) with regular velocity fields around NGC 2292/3 (Barnes 1999; Barnes & Webster 2001) and IC 2006 (Franx et al. 1994).

The purpose of this paper is to propose that there is a physical/evolutionary link between the massive isolated HI gas without apparent optical counterparts (e.g., HIPASS

* We adopt a distance of $D = 15.5$ Mpc for the NGC 2442 galaxy group (see Ryder et al. 2001).

Table 1. Model parameters and results on intragroup ring formation

No.	M_s ($\times 10^8$ $M_\odot$)	M_{dm}/M_s	M_g/M_s	R_s (kpc)	R_g/R_s	X_g (kpc)	V_g	model description	ring characteristics
M1	7.8	20	4	6.4	5	200	$0.75V_c$	fiducial	ring/arc
M2	7.8	20	10	6.4	5	200	$0.75V_c$	more massive	rings with star formation
M3	7.8	20	4	4.0	5	200	$0.75V_c$	HSB disk	no remarkable rings
M4	7.8	20	4	6.4	2	200	$0.75V_c$	compact HI disk	no remarkable rings
M5	7.8	20	4	6.4	5	200	$0.50V_c$	smaller pericenter	more massive rings

J0731-69) and the intragroup HI ring (e.g., the Leo ring). Using numerical simulations, we first demonstrate that intragroup HI rings or arcs can be formed from the outer gaseous envelope of a galaxy interacting with a group potential. Then we show that only the highest-density regions of the intragroup rings/arcs are generally observable in HI emission. In the following discussions, the theoretical 5σ HI column density of HIPASS (for a velocity width of 100 km s^{-1}) is 4×10^{18} atoms cm^{-2} for extended objects filling the beam (see Koribalski et al. 2004).

2 THE MODEL

We consider a bulgeless late-type galaxy (here a LSB) with an extended HI gas disk orbiting the center of the group and thereby numerically investigate the evolution of the outer HI disk. The galaxy orbit is determined solely by the fixed external gravitational field of the group with the scale-free logarithmic potential of $\Phi \equiv {V_c}^2 \log(r)$, where r denotes the distance of the galaxy from the group center. The adopted smooth potential with no substructures of the group might be an oversimplified assumption. Since we intend to discuss later the isolated HI gas discovered in the NGC 2442 galaxy group, we choose a reasonable and realistic value of V_c for this group. By assuming that the group center is nearly coincident with the center of the central elliptical galaxy NGC 2434 in this group, we choose 300 km s^{-1} (Rix et al. 1997) as a reasonable V_c. The initial orbital plane of the galaxy is the same as the x-z plane and the stellar and gaseous disk are initially inclined θ_d degrees with respect to the x-y plane. The initial position and velocity of the galaxy are therefore (X_g, 0, 0,) and (0, V_g, 0), respectively, where X_g and V_g are free parameters which determine the orbit of the galaxy. For most of models, $\theta_d = 45^\circ$, $X_g = 200$ kpc, and $V_g = 0.75V_c$ (see Table 1).

A late-type disk with the total stellar mass M_s is assumed to be embedded in a massive dark matter halo with a universal 'NFW' profile (Navarro et al. 1996) and the mass M_{dm}. The disk consists of an exponential *stellar disk* of size R_s, radial scale length 0.2 R_s, and mass M_s as well as a uniform (or exponential) *gas disk* of size R_g and mass M_g. M_s, M_{dm}/M_s, M_g/M_s, R_s, and R_g/R_s are important free parameters in the present study. Star formation in gas disk is modeled according to the Schmidt law (Schmidt 1959) with the exponent of 1.5. The coefficient of the law is chosen such that the mean star formation rate of the Galactic disk model with gas mass fraction of 0.1 is ~ 1 $M_\odot$ yr^{-1} for ~ 1 Gyr dynamical evolution of the disk (e.g., Bekki et al. 2002). These values in the star formation model are consistent with observations (e.g., Kennicutt 1998).

We mainly present the results of the 'fiducial' model (M1 in Table 1) with $M_s = 7.8 \times 10^8 M_\odot$ (correspond-

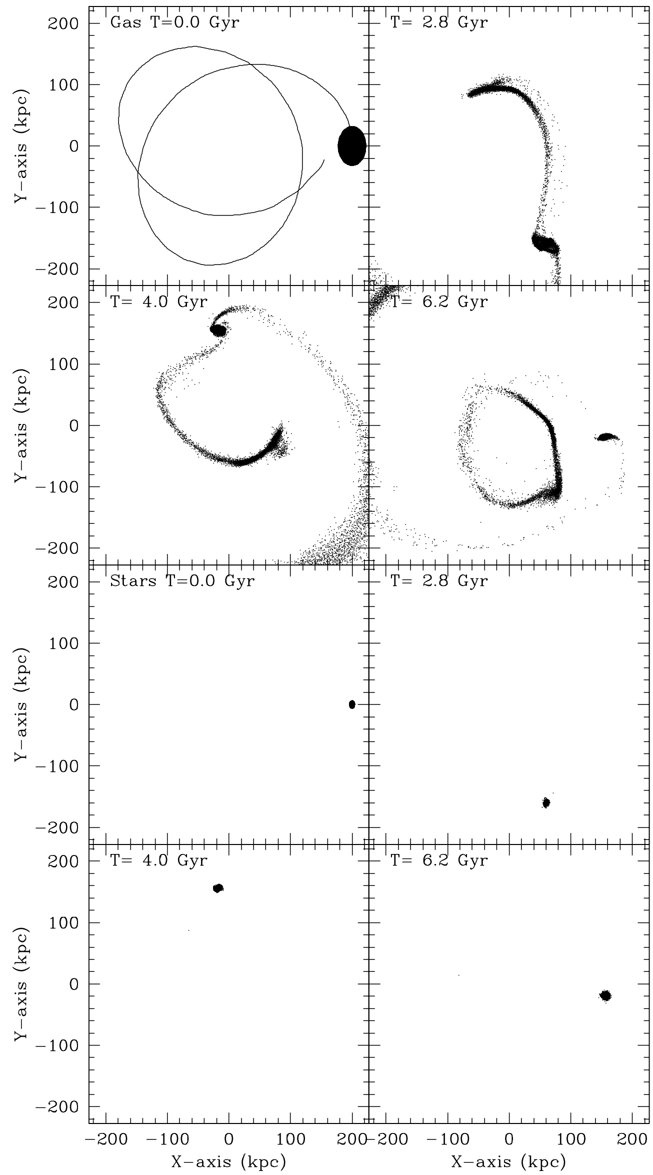

Figure 1. Morphological evolution of a low surface brightness (LSB) galaxy with an *extended HI disk* orbiting the center of the group in the fiducial model (M1 in Table 1), projected onto the x-y plane. The gaseous component is shown at the top, the stellar component at the bottom. The center of the group is at $(x, y) =$ (0,0) for all panels. The orbital evolution of the LSB galaxy is given by a solid line in the upper left panel. T represents the time that has elapsed since the start of the simulation. Note that a giant intragroup HI ring of size $\sim$200 kpc is formed at $T = 6.2$ Gyr and contains no stars. The size, the location with respect to the center of the group, the total mass, and the rotational kinematics of the ring at $T = 6.2$ Gyr are similar to those of the Leo ring (Schneider et al. 1989).

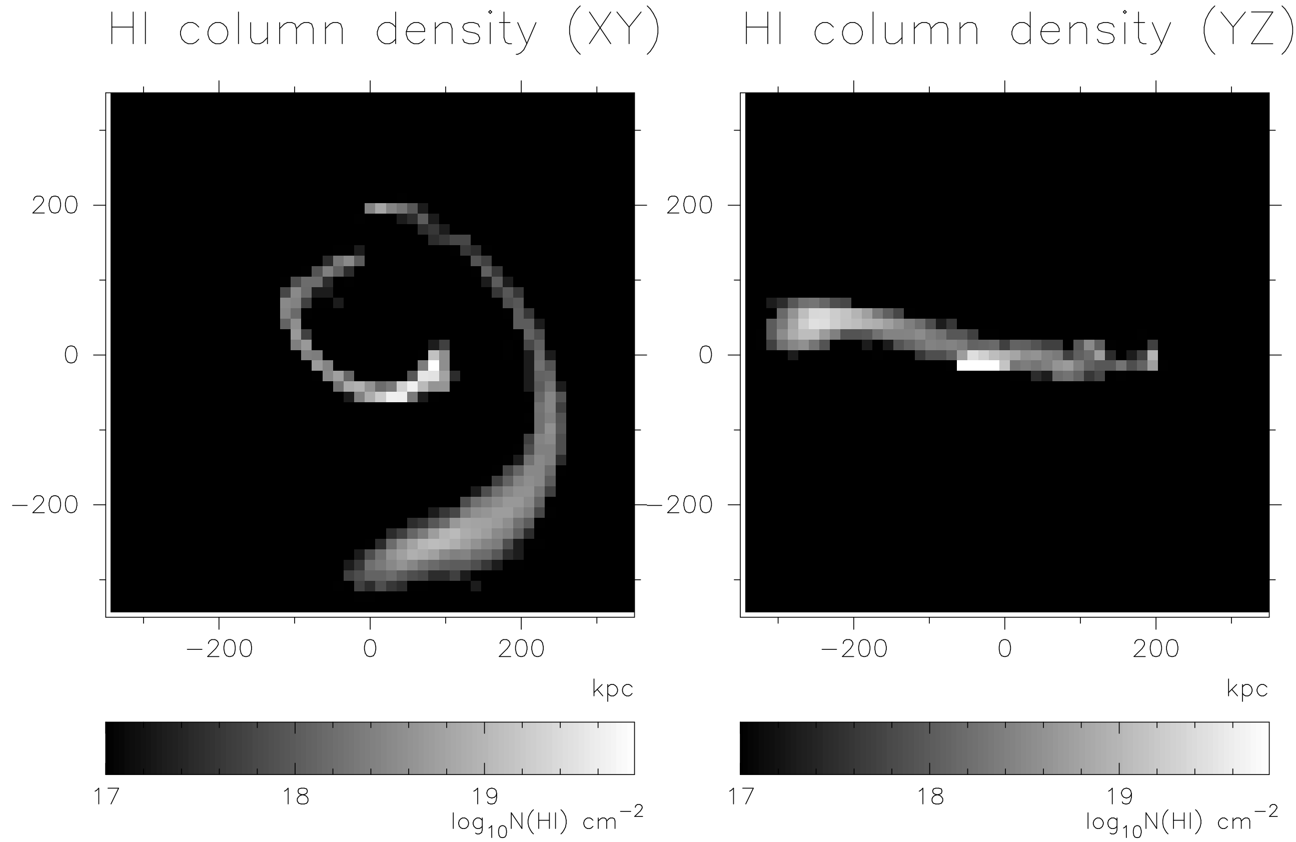

Figure 2. HI column density distribution ($N_{\rm HI}$) of the simulated intragroup ring/arc projected onto the x-y plane (left) and the y-z plane (right) in the fiducial model at $T = 4.0$ Gyr. Here only 'stripped gas particles' that are outside the initial HI gas disk of the LSB galaxy are used to estimate the column density. The cell size is 28 kpc. Cells with $N_{\rm HI} \leq 10^{17}$ atoms cm^{-2} (including those without gas particles, i.e., zero column density) are shown in black.

ing to $M_{\rm B} = -16$ mag), $M_{\rm dm}/M_{\rm s} = 20$, $M_{\rm g}/M_{\rm s} = 4$, $R_{\rm s} = 4$ kpc (i.e., a B-band central surface brightness of 24.5 mag arcsec^{-2}), and $R_{\rm g}/R_{\rm s} = 5$, i.e. a LSB galaxy with an HI disk five times larger than the stellar disk.

The HI diameters of gas-rich galaxies are generally observed to be larger than their optical disks (Broeils & van Woerden 1994). A small fraction of low luminosity galaxies have HI gas envelopes extending out to 4–7 $R_{\rm s}$ (e.g., Hunter 1997) with HI mass to light ratios up to $\sim 20 {\rm M}_{\odot}\ {\rm L}_{\odot}^{-1}$ (Warren et al. 2004). Therefore, the above parameter set can be regarded as reasonable. Parameter values of other representative models are shown in Table 1. All models include the hydrodynamical evolution of the isothermal gas; they are investigated using TREESPH codes described in Bekki (1997). The resolution of each simulation is $\sim 1.6 \times 10^5 {\rm M}_{\odot}$ for mass and $\sim$ 200 pc for scale. Individual time step is allocated for each particle with the maximum time step width of 1.4×10^6 yr.

3 RESULTS

Fig. 1 describes how gaseous intragroup rings/arcs are formed from the galaxy-group interaction in the fiducial model. As the LSB galaxy passes by the pericenter of its orbit for the first time, the group's strong tidal field efficiently strips the outer HI disk of the LSB galaxy ($T = 2.8$ Gyr). The stripped HI disk or 'leading stream' can orbit the group center and consequently forms an arc-like structure with a size of ∼200 kpc with a very inhomogeneous density distribution ($T = 4.0$ Gyr). The total mass of the HI arc (i.e., stripped HI) is $1.4 \times 10^9 M_{\odot}$ (43% of the initial HI mass) with only 11% of the initial gas converted into new stars mostly within the optical disk ($T = 4.0$ Gyr). The projected surface gas density $\Sigma_{\rm g}$ (or column density $N_{\rm HI}$) ranges from 1.0×10^{17} atoms cm^{-2} to 1.1×10^{20} atoms cm^{-2} along the inner arc. The HI disk size of the LSB galaxy is dramatically reduced (from ∼5 $R_{\rm s}$ to ∼2 $R_{\rm s}$) because of the tidal stripping of the outer part of the HI disk.

The stellar disk of the LSB galaxy, on the other hand, is less susceptible to the tidal field of the group than the gas so that stellar tidal tails are not formed in the galaxy-group interaction. Finally, an HI gas ring without stars is formed around the center of the group ($T = 6.2$ Gyr). It should be stressed here that the LSB galaxy, from which the HI ring originated, is located well outside the ring so that there appears to be no physical connection between them. Fig. 2 shows the HI column density distribution of the ring at $T = 4.0$ Gyr. Since HI column density along the ring/arc is very inhomogeneous, only the highest density regions such as the tip of the ring/arc can be detected in currently ongoing observations for both face-on and edge-on views. For example, the number fraction of cells with $\Sigma_{\rm g} \geq 4 \times 10^{18}$ atoms cm^{-2} corresponding roughly to the

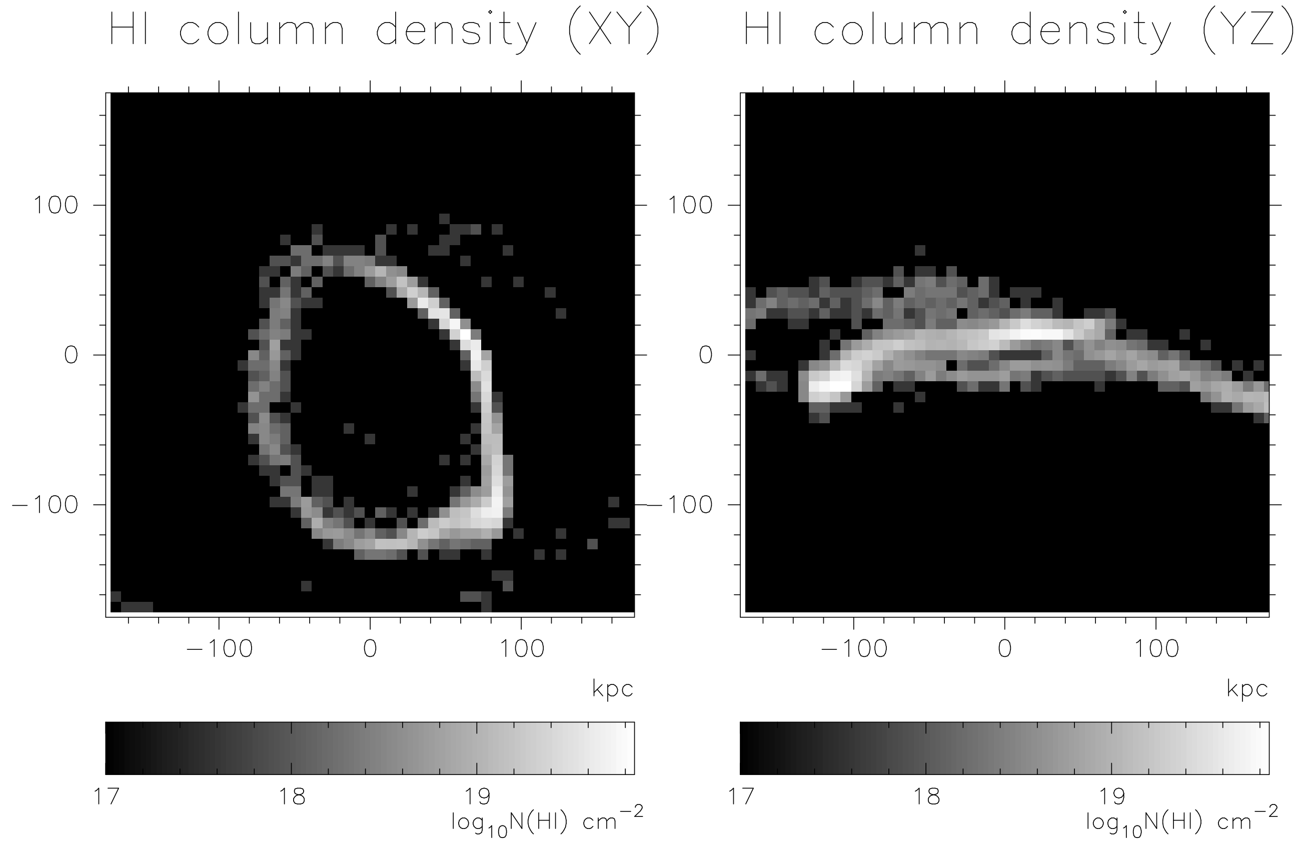

Figure 3. The same as Fig. 2 but for $T = 6.2$ Gyr.

HIPASS detection limit is only 23 % among all cells with $\Sigma_g \geq 10^{17}$ atoms cm^{-2}. However, Fig. 2 also indicates that if the detection limit in future observations is as good as $\sim 10^{17}$ atoms cm^{-2}, evidence for the ring/arc structures should be revealed. Fig. 3 also demonstrates that the intragroup ring has a very inhomogeneous density distribution, which is consistent with observations of some intragroup HI rings such as the Leo ring (e.g., Schneider et al. 1989).

Physical properties of the simulated intragroup rings/arcs in other 4 representative models (M2−M5) are described as follows. Firstly, in the model M2 where the LSB galaxy initially has a larger amount of HI gas in the disk ($\sim 8 \times 10^9 M_\odot$), stars form in parts of the HI rings/arcs (See Fig. 4). This is due essentially to the increased HI gas density in the ring as compared to the model M1. HI clouds containing young and new stars can be identified as intergalactic HII regions. Secondly, intergalactic HI rings/arcs *with no optical counterparts* (i.e., without stellar streams) can neither be seen in the model M3 with HSB disk nor in M4 with more compact HI disk. This is because (1) tidal stripping of the outer HI gas is much less efficient in this HSB-group interaction and (2) most of the gas is consumed by star formation due to initial high density of gas within the disks (i.e., little gas can be stripped). Thirdly, the larger amount of gas is stripped to form a more massive ring in the model M5 with smaller pericenter of the LSB. This implies that total masses of intragroup HI rings/arcs formed from galaxy-group interaction depend strongly on the orbits of galaxies with respect to the group center for a given galactic mass. Furthermore,

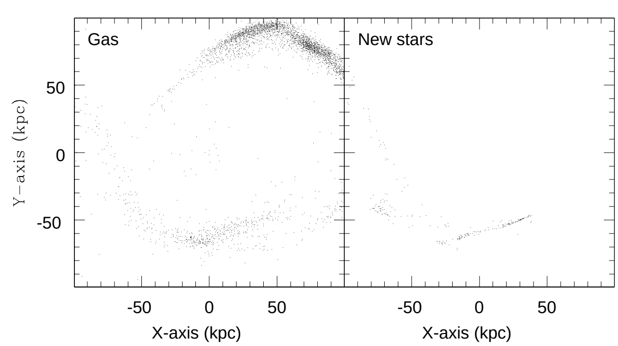

Figure 4. Mass distributions of gas (left) and new stars formed from gas (right) along the intragroup ring projected onto the x-y plane at $T = 4.5$ Gyr for the model M2 (see Table 1) with the initial gas mass 2.5 times larger than that of the fiducial model. Note that gas density appears to be lower in the gaseous regions where young stars are located (i.e., in the lower HI arc).

the HI disk sizes of galaxies with smaller pericenter are more significantly reduced during galaxy-group interaction.

4 DISCUSSIONS AND CONCLUSIONS

We have demonstrated that (1) gaseous intragroup rings/arcs can be formed by dynamical interaction between LSB galaxies *with extended HI disks* and the group potential and (2) due to their inhomogeneous density distribution only the high-density peaks within these rings/arcs can currently be observed as apparently isolated clumpy HI clouds. This 'tip of the iceberg' scenario can not only explain why the observed massive intragroup HI clouds (e.g., Ryder et al. 2001) do not have any detectable optical counterparts but also provide a clear explanation for the origin of HI rings such as the Leo ring (Schneider et al. 1989). This scenario predicts that there would be less massive intragroup HI rings/arcs that have not been identified as 'rings/arcs' in observational studies for HI gas of groups of galaxies because of their low HI gas density. *Some* high velocity clouds (HVCs) observed in the Local Group and other galaxy groups can be high-density parts of intragroup rings/arcs.

The present numerical models predict the existence of isolated intergalactic star-forming regions located within the high density parts of intragroup (intergalactic) HI rings/arcs formed from galaxy–group (galaxy–galaxy) interaction. These star-forming regions, which do not have an old stellar population, are in striking contrast to 'tidal dwarf galaxies'. Both theory and observations suggested that tidal dwarfs are formed in the tidal tails of interacting/merging galaxies thus have old and new stars but no dark matter (e.g., Duc & Mirabel 1998; Duc et al. 2000). Recently, Ryan-Weber et al. (2004) found a number of very small isolated HII regions at projected distances up to 30 kpc from their nearest galaxy (e.g., NGC 1533), but located well within the tidal HI features. Oosterloo et al. (2004) also found HII regions associated with the HI clouds near NGC 1490. In the Leo Ring (Schneider et al. 1989) no Hα has so far been detected (Donahue et al. 1995).

Our simulations furthermore suggest that the size of extended outer HI disks in galaxies is related to their environment and interaction history. Although both sizes and morphological properties of outer HI gas disks are observed to vary significantly between gas-rich galaxies (e.g., Broeils & van Woerden 1994; Broeils & Rhee 1997), the origin of this diversity remains elusive (Broeils & Rhee 1997). The present numerical results have shown that the size of the HI disk of a galaxy interacting with its host group can be significantly reduced and the reduction rate depends on the galactic orbit. These results suggest that sizes of the outer HI gas disks in galaxies can be "fossil records" of past dynamical interaction with its host group.

The present study suggests that future high sensitivity HI observations (e.g., the upgraded Arecibo telescope with HI detection limit of at least 10^{17} atoms cm^{-2}) will reveal faint intragroup rings/arcs in which the observed massive HI gas clouds are embedded. Extensive structural and kinematical studies on the intragroup rings/arcs connected to the isolated clouds will enable us to give strong constraints on the orbital evolution of galaxies from which HI gas was stripped due to group-galaxy interaction. Thus future observational studies on intragroup HI rings/arcs, combined with numerical simulations with variously different sets of orbital parameters of galaxies in groups, will provide valuable information on the roles of galaxy-group interaction in galaxy evolution in groups of galaxies.

5 ACKNOWLEDGMENT

We are grateful to the referee for valuable comments, which contribute to improve the present paper. KB and WJC acknowledge the financial support of the Australian Research Council throughout the course of this work. All of the simulations described here were performed on NEC SX5/2 systems at AC3 (Australian Centre for Advanced Computing and Communications).

REFERENCES

Barnes, D. G. 1999, PASA, 16, 77
Barnes, D. G., Webster, R. 2001, MNRAS, 324, 859
Bekki, K. 1997, ApJ, 483, 608
Bekki, K., Forbes, Duncan A., Beasley, M. A., Couch, W. J. 2002, MNRAS, 335, 1176
Beuing, J., Döbereiner, S., Böhringer, H., Bender, R. 1999, MNRAS, 302, 209
Broeils, A. H., van Woerden, H. 1994, A&AS, 107, 129
Broeils, A. H., Rhee, M.-H. 1997, A&A, 324, 877
Donahue, M., Aldering, G., Stocke, J. T., 1990, ApJ, 450, L45
Duc, P.-A., Mirabel, I. F. 1998, A&A, 333, 813
Duc, P.-A., Brinks, E., Springel, V., Pichardo, B., Weilbacher, P., Mirabel, I. F. 2000, AJ, 120, 1238
English, J., Koribalski, B.S., Freeman, K.C. 2004, in 'Recycling Intergalactic and Interstellar Matter', IAU Symposium Series, Vol. 217, eds. P.-A. Duc, J. Braine and E. Brinks, p41.
Franx, M., van Gorkom, J.H., de Zeeuw, P.T. 1994, ApJ 436, 642
Hibbard, J.E., van Gorkom, J.H., Rupen, M.P., Schiminovich, D. 2001, in 'Gas and Galaxy Evolution', ASP Conf. Series, Vol. 240, eds. J.E. Hibbard, M.P. Rupen, and J.H. van Gorkom, p. 659
Hunter, D. A. 1997, PASP, 109, 937
Kennicutt, Robert C., Jr. 1998, ARA&A, 36, 189
Koribalski, B. S., Staveley-Smith, L., Kilborn, V.A. et al., 2004, AJ, 128, 16
Koribalski, B., Gordon, S., Jones, K. 2003, MNRAS 339, 1203
Koribalski, B. 2004, in 'Recycling Intergalactic and Interstellar Matter', IAU Symposium Series, Vol. 217, eds. P.-A. Duc, J. Braine and E. Brinks, p34.
Malphrus, B.K., Simpson, C.E., Gottesman, S.T., Hawarden T.G. 1997, AJ 114, 1427
Navarro, J. F., Frenk, C. S., White, S. D. M., 1996, ApJ, 462, 563
Oosterloo, T., Sadler, E., Morganti, R., Ferguson, A., Jerjen, H. 2004, in 'Recycling Intergalactic and Interstellar Matter', IAU Symposium Series, Vol. 217, eds. P.-A. Duc, J. Braine and E. Brinks, p486. (astro-ph/0310632)
Putman, M.E., Staveley-Smith, L., Freeman, K.C., Gibson, B.K., Barnes, D.G. 2003, ApJ, 586, 170
Rix, H-W., de Zeeuw, P. T., Cretton, N., van der Marel, R. P., Carollo, C. M. 1997, ApJ, 488, 702
Ryan-Weber, E., Webster, R., Bekki, K. 2003, in 'The IGM/Galaxy Connection: The Distribution of Baryons at z=0', ASSL Conference Proceedings Vol. 281, eds. J. L. Rosenberg and M. E. Putman, Kluwer Academic Publishers, Dordrecht, p. 223
Ryan-Weber, E., et al. 2004, AJ, 127, 1431
Ryder, S., Koribalski, B., et al. 2001, ApJ, 555, 232
Schmidt, M. 1959, ApJ, 129, 243
Schneider, S.E., et al. 1989, AJ 97, 666
Warren, B. E., Jerjen, H., Koribalski, B. S. 2004, AJ, 128, 1152
Yun, M., Ho, P., Lo, K. 1994, Nature 372, 530