Ram-pressure stripping of halo gas in disc galaxies: implications for galactic star formation in different environments

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ABSTRACT

We numerically investigate the evolution of gaseous haloes around disc galaxies in different environments, ranging from small groups to rich clusters, in order to understand galaxy evolution in these environments. Our simulations self-consistently incorporate the effects of ram pressure of the intergalactic medium (IGM) on the disc and halo gas of galaxies and hydrodynamical interaction between disc and halo gas, so that the mass fractions of halo gas stripped by ram pressure of the IGM ($F_{\text{strip}}$) can be better estimated. We mainly investigate how $F_{\text{strip}}$ depends on the total masses of the host environments ($M_{\text{host}}$), galactic masses ($M_{\text{gal}}$), densities and temperature of the IGM (T$_{\text{IGM}}$ and $\rho_{\text{IGM}}$, respectively), the relative velocities between the IGM and galaxies ($V_r$) and the physical properties of discs (e.g. gas mass fraction). We find that typically 60–80 per cent of halo gas can be efficiently stripped from Milky-Way-type disc galaxies by ram pressure in clusters with $M_{\text{host}}$ ~ $10^{14}$ M$_\odot$. We also find that $F_{\text{strip}}$ depends on $M_{\text{host}}$ such that $F_{\text{strip}}$ is higher for larger $M_{\text{host}}$. Furthermore, it is found that $F_{\text{strip}}$ can be higher in disc galaxies with smaller $M_{\text{gal}}$ for a given environment. Our simulations demonstrate that the presence of disc gas can suppress ram-pressure stripping of halo gas, owing to hydrodynamical interaction between halo and disc gas. Ram-pressure stripping of halo gas is found to be efficient (i.e. $F_{\text{strip}} > 0.5$) even in small and/or compact groups, if $\rho_{\text{IGM}}$ ~ $10^5$ M$_\odot$ kpc$^{-3}$ and $V_r$ ~ 400 km s$^{-1}$. Based on the derived radial distributions of the remaining halo gas after ram-pressure stripping, we propose that the truncation of star formation after halo-gas stripping can occur from the outside in in disc galaxies. We suggest that although the gradual truncation of star formation in disc galaxies can occur in groups, this proceeds less rapidly in comparison with cluster environments. We also suggest that low-mass galaxies are likely to truncate their star formation more rapidly, owing to more efficient halo-gas stripping in groups and clusters.

Key words: galaxies: haloes – galaxies: kinematics and dynamics – galaxies: structure.

1 INTRODUCTION

Since Larson, Tinsley & Caldwell (1980) discussed the removal of galactic halo gas from disc galaxies in terms of transformation from spirals into S0s, many observational and theoretical works have investigated the evolution of galactic halo gas in various different aspects of galaxy evolution, such as the maintenance of spiral arms by halo-gas infall (e.g. Sellwood & Carlberg 1984), the formation of passive spiral galaxies in groups and clusters (e.g. Bekki, Couch & Shioya 2002) and the colour evolution of satellite galaxies entering their host group- and cluster-scale haloes (e.g. Font et al. 2008). One important suggestion from these previous works is that the stripping of galactic halo gas can cause severe suppression of galactic global star formation in different environments (‘strangulation’: Balogh et al. 1999; Balogh, Navarro & Morris 2000). Although the strangulation scenario can explain a number of recent observational results, such as the presence of red passive spirals in distant clusters (e.g. Couch et al. 1998; Dressler et al. 1999; Poggianti et al. 1999, 2008) and a mean star-formation rate dependent on galaxy environments (e.g. Balogh et al. 2004), it is still unclear why and how effective strangulation can occur in different environments (e.g. groups and clusters).

Previous theoretical and numerical studies have tried to understand how galactic halo gas responds to environmental effects, such as the tidal fields of groups and clusters (e.g. Bekki, Couch & Shioya 2001) and ram-pressure stripping of the intergalactic medium (IGM) (Balogh et al. 2000; Bekki et al. 2002; Hester 2006; McCarthy et al. 2008). Although these works discussed quantitatively how great a fraction of halo gas can be removed from galaxy-scale haloes by ram...
pressure of the IGM in their host environments, their models are not very sophisticated at some points. For example, previous numerical models (e.g. Bekki et al. 2002) do not adopt realistic galaxy models with stellar and gaseous discs, and ignore the hydrodynamical interaction between halo and disc gas. More sophisticated numerical models are required to discuss more qualitatively how great a fraction of halo gas can be removed by ram-pressure stripping and whether and how hydrodynamical interaction between the halo and disc gas can influence ram-pressure stripping of halo gas in disc galaxies.

The purpose of this paper is thus to investigate the time-evolution of galactic halo gas in disc galaxies under moderately strong ram pressure of the IGM in their host environments, based on more sophisticated numerical simulations. We focus mainly on (i) the final mass fractions of halo gas stripped from disc galaxies (\(F_{\text{strip}}\)), (ii) the radial properties of the halo gas and (iii) the dependences of (i) and (ii) on the physical properties of galaxy environments (e.g. the total masses of groups and clusters). The present results can be used for interpreting observational results regarding the spatial distribution of hot halo gas in galaxies (e.g. Jeltema, Binder & Mulchaey 2008), the physical properties of passive spirals in groups and clusters (e.g. Poggianti et al. 2008; Bamford et al. 2009) and the origin of the possible suppression of star formation in compact groups (e.g. Rasmussen et al. 2008).

The structure of the paper is as follows. In the next section, we describe our numerical models for ram-pressure stripping of galactic halo gas. In Section 3, we present our numerical results, mainly on the physical properties of the remaining halo gas after ram-pressure stripping for various different models. In Section 4, we compare the present results with those from other authors and discuss the implications of the present results. We summarize our conclusions in Section 5. We do not discuss ram-pressure stripping of disc gas in galaxies in an extensive manner here, because a number of authors have already discussed the stripping processes in detail (e.g. Abadi, Moore & Bower 1999; Marcolini, Brighenti & D’Ercole 2003; Vollmer et al. 2006; Kronberger et al. 2008; Roediger & Brüggen 2008; Tonnesen & Bryan 2008).

2 THE MODEL

2.1 Disc galaxy

In order to simulate the time-evolution of galactic halo gas under ram pressure of the IGM, we use the latest version of GRAPE (Gravity Pipe, GRAPE-7), which is the special-purpose computer for gravitational dynamics (Sugimoto et al. 1990). We use our original GRAPE-SPH code (Bekki & Chiba 2006), which combines the method of smoothed particle hydrodynamics (SPH) with GRAPE, for calculations of three-dimensional self-gravitating fluids in astrophysics. The original code used in our previous studies is here revised so that both (i) ram-pressure effects of a hot IGM on galactic halo gas and (ii) hydrodynamical interaction between halo and disc gas can be investigated in a fully self-consistent manner. Fig. 1 illustrates the initial configurations for halo and disc gas in a disc galaxy and the hot IGM surrounding the disc galaxy in the present numerical study.

Since our numerical methods for modelling the dynamical evolution of Milky-Way-type disc galaxies have already been described by Bekki & Shioya (1998) and by Bekki & Peng (2006), we give only a brief review here. The total disc mass and the size of the disc of a Milky-Way-type disc galaxy with total mass \(M_{\text{gal}}\) are \(M_d\) and \(R_g\), respectively. Henceforth, all masses and lengths are measured in units of \(M_d\) and \(R_d\), respectively, unless specified. Velocity and time are measured in units of \(v = (G M_d/R_d)^{1/2}\) and \(t_{\text{dyn}} = (R_d^3/G M_d)^{1/2}\), respectively, where \(G\) is the gravitational constant and assumed to be 1.0 in the present study.

If we adopt \(M_d = 6.0 \times 10^{10} M_\odot\) and \(R_d = 17.5 \text{kpc}\) as a fiducial value, then \(v = 1.21 \times 10^2 \text{km s}^{-1}\) and \(t_{\text{dyn}} = 1.41 \times 10^8 \text{yr}\), respectively. The disc is composed of a dark matter halo, a stellar disc, a stellar bulge, a gaseous disc and a gaseous halo.

The mass ratio of the dark matter halo to the stellar disc in a disc model is fixed at 16.7 models (i.e. \(M_{\text{gal}}/M_d = 17.7\)). We adopt the density distribution of the Navarro, Frenk & White (1996, hereafter NFW) halo suggested from cold dark matter (CDM) simulations:

\[
\rho(r) = \frac{\rho_0}{(r/r_c)(1 + r/r_c)^2},
\]

where \(r\), \(\rho_0\), and \(r_c\) are the spherical radius, the characteristic density of a dark halo and the scalelength of the halo, respectively. The value of \(r_c\) (0.6 in our units for \(c = 10\)) is chosen such that the rotation curve of a disc is reasonably consistent with observations. The mass fraction and the scalelength of the stellar bulge represented by the Hernquist profile are fixed at 0.17 (i.e. 17 per cent of the stellar disc) and 0.04 (i.e. 20 per cent of the scalelength of the stellar disc), respectively, which are consistent with those of the bulge model of the Galaxy.

The radial \((R)\) and vertical \((Z)\) density profiles of the disc are assumed to be proportional to \(\exp(-R/R_0)\) with scalelength \(R_0 = 0.2\) and to \(\sech^2(Z/Z_0)\) with scalelength \(Z_0 = 0.04\) in our units, respectively; both stellar and gaseous discs follow this exponential distribution. In addition to the rotational velocity caused by the gravitational field of disc, bulge and dark halo components, the initial radial and azimuthal velocity dispersions are assigned to the disc component according to epicyclic theory with Toomre’s parameter \(Q = 1.5\). The vertical velocity dispersion at a given radius is set to be 0.5 times as large as the radial velocity dispersion.
at that point, as is consistent with the observed trend of the Milky Way (e.g. Wielen 1977).

We investigate models with different $M_{\text{gal}}$ and adopt Freeman’s law (Freeman 1970) to determine the $R_0$ of a disc galaxy according to its disc mass:

$$R_0 = 3.5 \left( \frac{M_d}{6 \times 10^{10} M_\odot} \right)^{0.5} \text{kpc}. \quad (2)$$

Structural and kinematical properties of dark matter haloes and stellar discs are assumed to be self-similar between models with different $M_{\text{gal}}$. The gas mass fraction ($f_g$) is assumed to be a free parameter. An isothermal equation of state is used for gas with temperatures of $10^4 \text{K}$ for models with $M_{\text{gal}} = 6 \times 10^{10} M_\odot$. The initial temperature ($T_{\text{gas}}$) of the disc gas is assumed to be scaled to $T_{\text{gas}} \propto M_{\text{gal}}^{0.5}$.

### 2.2 Halo gas and hot IGM

The gaseous halo has mass $M_{\text{halo}}$ and the same spatial distribution as the dark matter, and is assumed to be initially in hydrostatic equilibrium. The initial gaseous temperature of a halo-gas particle is therefore determined by the gas density, total mass and gravitational potential at the location of the particle via Euler’s equation for hydrostatic equilibrium (e.g. equation (IE-8) in Binney & Tremaine 1987). Therefore gaseous temperature $T_{\text{halo}}(r)$ at radius $r$ from the centre of a disc galaxy can be described as

$$T_{\text{halo}}(r) = \frac{m_p}{k_B} \int_0^r \rho_{\text{halo}}(r) \frac{GM(r)}{r^2} \, dr,$$

where $m_p$, $G$, and $k_B$ are the proton mass, the gravitational constant and the Boltzmann constant, respectively, and $M(r)$ is the total mass within $r$ determined by the adopted mass distributions of dark matter and baryonic components in the disc galaxy. Radiative cooling is not included in the present study, so that the hydrodynamical equilibrium of halo gas can be obtained in isolated disc models; if gaseous cooling is included in a disc model, the halo gas can rapidly collapse to set down directly on to the gas disc so that the physical role of ram-pressure stripping in the evolution of halo gas cannot be properly investigated. The present idealized models thus help us to grasp some essential ingredients of the physical roles of a hot IGM in the evolution of galactic halo gas.

Sembach et al. (2003) showed that the gaseous halo of the Galaxy is highly extended ($R \sim 70 \text{kpc}$) and low-density ($\rho_{\text{halo}} \sim 10^{-1} - 10^{-5} \text{cm}^{-3}$). It is, however, observationally unclear how far galactic halo gas extends in other galaxies. We therefore consider that the radius of the galactic halo ($R_{\text{halo}}$) is a free parameter. Guided by the above observational results by Sembach et al. (2003), we mainly investigate models with $R_{\text{halo}} = 3 - 6 R_d$ and $\rho_{\text{halo}} = 10^{-4} \text{cm}^{-3}$.

The disc galaxy is assumed to be embedded in a hot IGM with temperature $T_{\text{IGM}}$ and density $\rho_{\text{IGM}}$. In order to avoid huge particle numbers being required to represent the entire IGM in groups and clusters of galaxies (e.g. Abadi et al. 1999), the IGM is represented by SPH particles with velocities of $V_r$ in a cube with size $R_{\text{IGM}}$. The initial velocity of each SPH particle for the IGM is set to be $(V_r, 0, 0)$ for all models (i.e. the particle flows along the $x$-axis to the positive $x$ direction). The IGM has a uniform distribution within the cube and $R_{\text{IGM}}$ is set to be $10 M_d$ for models with $R_{\text{halo}} = 3 R_d$. We include periodic boundary conditions (at $R_{\text{IGM}}$) for the IGM SPH particles leaving the cube. The parameter values $T_{\text{IGM}}$ and $\rho_{\text{IGM}}$ are chosen based on the adopted total masses of the galaxy host environment ($M_{\text{halo}}$).

The spin of the disc galaxy is specified by two angles $\theta$ and $\phi$ (in units of degrees), where $\theta$ is the angle between the $z$-axis and the vector of the angular momentum of the disc, and $\phi$ is the azimuthal angle measured from the $x$-axis to the projection of the angular momentum vector of the disc on to the $x$-$y$ plane. In order to show more clearly ram-pressure effects on galactic halo gas, we mainly investigate models with $\theta = 90^\circ$ and $\phi = 0^\circ$, in which the entire gas disc can strongly feel the ram pressure of the IGM. We also investigate models with different $\theta$ and $\phi$ to clarify the roles of halo-disc hydrodynamical interaction in keeping halo gas within disc galaxies.

The mass resolution for disc-gas particles, halo-gas particles and the IGM in luminous disc models with $M_d = 6 \times 10^{10} M_\odot$ yields $3.5 \times 10^5 M_\odot$, $5.9 \times 10^5 M_\odot$ and $0.3 \times 10^5 M_\odot$, respectively. The smoothing length for disc-gas particles (the mean smoothing length at $T = 0.21 \text{Gyr}$) in the standard model is $680 \text{pc}$ (this can be as large as $4.7 \text{kpc}$ for halo-gas particles, owing to the stripped halo gas).

### 2.3 Parameter study

Although we have investigated 45 models with different $M_{\text{gal}}$, $f_g$, $V_r$, $\rho_{\text{IGM}}$ and $T_{\text{IGM}}$, we mainly show the results of the ‘standard’ model with $M_{\text{gal}} = 1.1 \times 10^{12} M_\odot$, $f_g = 0.1$, $V_r = 500 \text{km} \text{s}^{-1}$, $\rho_{\text{IGM}} = 10^5 M_\odot \text{kpc}^{-3}$ and $T_{\text{IGM}} = 10^7 \text{K}$. This is mainly because the standard model can clearly show the typical behaviour of ram-pressure stripping of halo gas from disc galaxies. For a canonical baryonic mass fraction of $0.14 \left(\equiv \Omega_b/\Omega_m\right)$ in the Universe, $\rho_{\text{IGM}}$ can be as high as $10^5 M_\odot \text{kpc}^{-3}$ at $r \sim 100 \text{kpc}$ in a cluster with the NFW profile, total mass $10^{14} M_\odot$ and a virial velocity ($v_{\text{eq}}$) of 500–600 km s$^{-1}$. We thus consider that the adopted values of $\rho_{\text{IGM}}$, $V_r$ and $T_{\text{IGM}}$ are reasonable for a cluster of galaxies with $M_{\text{host}} = 10^{14} M_\odot$. It should be stressed here that the strength of the ram pressure ($P_{\text{ram}}$) in the standard model is much weaker than that required for ram-pressure stripping of disc gas in the central regions of clusters (e.g. Abadi et al. 1999). The adopted galaxy mass in the standard model is referred to as $M_{\text{low}}$ just for convenience.

The total number of particles used for the disc galaxy and the IGM in the standard model are 133,699 and 125,000, respectively. The present simulation requires typically 70–160 CPU hours of the adopted GRAPE-7 systems for each model, depending on model parameters: we have adopted the above particle numbers to run numerous models within a reasonable time-scale. We have conducted a resolution test by using a high-resolution model with the total particle number 333,805 and found that there is only $\sim 7$ per cent difference in $F_{\text{strip}}$ between the standard model and the high-resolution one. We thus consider that the above particle number is enough to discuss ram-pressure stripping of halo gas around disc galaxies. Gravitational softening lengths in simulation units ($R_s$) are set to be fixed at 0.018 for the galaxy and 0.2 for the IGM. The range of model parameters investigated in the present study is shown in Table 1.

We divide our models into four categories: a ‘rich cluster’ model with $M_{\text{host}} = 10^{12} M_\odot$, a ‘cluster’ one with $M_{\text{host}} = 10^{12} M_\odot$, a ‘group’ one with $M_{\text{host}} = 10^{11} M_\odot$ and a ‘small-group’ one with $M_{\text{host}} = 10^{10} M_\odot$. Considering the virial velocities ($v_{\text{eq}}$) of dark matter haloes (NFW95) and the scaling relation between masses and sizes for dark matter haloes (e.g. Padmanabhan 1993), reasonable values of $T_{\text{IGM}}$ and $V_r$ are chosen for the above four models with different $M_{\text{host}}$. In the present study, the $V_r$ of the IGM in a galaxy environment with $M_{\text{host}}$ is set to be similar to the $v_{\text{eq}}$ of a dark matter halo with $M_{\text{host}}$. $T_{\text{IGM}}$ values in the small-group, group, cluster and rich-cluster models are $10^6$, $3.2 \times 10^6$, $10^7$ and $3.2 \times 10^7 \text{K}$, respectively, in the present study. $V_r$ values in the
Table 1. The ranges of model parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value ranges</th>
<th>$M_{\text{host}} \times M_{\odot}$</th>
<th>$V_r$ (km s$^{-1}$)</th>
<th>$\rho_{\text{IGM}} \times 10^5$ M$_{\odot}$ kpc$^{-3}$</th>
<th>$T_{\text{IGM}}$ (x10$^7$ K)</th>
<th>$f_g$</th>
<th>$R_{\text{halo}}$ (xR$_d$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.05–1.0</td>
<td>160–2000</td>
<td>0.1–5.0</td>
<td>0.1–3.2</td>
<td>0–0.1</td>
<td>1–6</td>
</tr>
</tbody>
</table>

$^a$ The total mass of a galaxy in units of $M_{\odot}$.

$^b$ The relative velocity of the hot IGM with respect to the galaxy.

$^c$ The initial mass density of the hot IGM in the cube.

$^d$ The initial temperature of the hot IGM in the cube.

$^e$ The initial gas mass fraction in a galactic disc.

$^f$ The initial radius of a spherical galactic halo gas of a disc galaxy in units of R$_d$, where R$_d$ is the disc size.

small-group, group, cluster and rich-cluster models are 158, 281, 500 and 889 km s$^{-1}$, respectively.

We mainly investigate the time-evolution of gas mass ($M_g$) for the halo and disc components in galaxies and the final mass fraction of halo gas stripped from galaxies ($F_{\text{strip}}$). We consider that if SPH gas particles at the final time-step of a simulation are outside $R_{\text{halo}}$, then they are regarded as being stripped by the ram pressure of the IGM. For most models, halo gas can be rapidly stripped from galaxies well within 0.5 Gyr. Therefore, we estimate $F_{\text{strip}}$ at $T = 0.56$ Gyr, where the time $T$ represents the time that has elapsed since the simulation started. We also estimate the accretion rate of gas on to the central 1 kpc of a disc galaxy in a simulation by dividing the total gas mass accumulated in the central 1 kpc at the final time-step by the time that has elapsed since the simulation started (i.e. 0.56 Gyr). We confirm that the accretion rates in different models do not depend much on model parameters in the present study.

3 RESULTS

3.1 The standard model

Fig. 2 shows how halo-gas responds to moderately strong ram pressure of the IGM in the standard model with $M_{\text{host}} = 10^{14}$ M$_{\odot}$, $T_{\text{IGM}} = 10^7$ K and $V_r = 500$ km s$^{-1}$. The halo gas is efficiently stripped from the disc galaxy to start to form a gaseous stream behind the galaxy within 0.14 Gyr. Owing to the presence of the disc gas, halo gas initially located in the inner halo can be accumulated above the disc and thus cannot be stripped from the galaxy. The gaseous stream, with many small clumps formed after stripping, can finally become less significant within 0.56 Gyr and most of the remaining halo gas can be located close to the disc. The final distribution of the halo gas appears to be more compact, flattened and inhomogeneous at $T = 0.56$ Gyr. The disc gas, on the other hand, cannot be stripped efficiently from the galaxy, because it is much more strongly bounded by the disc in comparison with the halo gas. Thus, ram-pressure stripping of halo gas is much more effective than that of disc gas.

Fig. 3 shows that 66 per cent and 6 per cent of the initial gas can be stripped from the halo and disc, respectively, by ram pressure within 0.56 Gyr for the standard model. Fig. 4 shows that halo gas initially in the inner halo ($R_{\text{hg, in}} < 10$ kpc) is more likely to be still located in the galaxy ($R_{\text{hg, in}} < R_{\text{halo}}$). The remaining halo gas might well be accreted later on to the inner region of the disc to increase the total gas mass of the disc slightly. The halo gas initially located in the outer halo ($R > R_d$) can be much more efficiently stripped by ram pressure. The stripping of the outer halo gas might well severely suppress the accretion of the gas on to the outer part of the disc.
of the galaxy and thus contribute to the truncation of star formation there.

Fig. 5 shows that the radial distribution of the halo gas can dramatically change after hydrodynamical interaction between the IGM and the halo gas, although that of the disc gas barely changes, owing to ram pressure weaker than the self-gravity of the gas disc. The distribution of halo gas becomes more compact with the half-mass radius of ~10 kpc at $T = 0.56$ Gyr, because the stripping can happen much more efficiently in the outer halo, where the halo is more susceptible to ram-pressure effects owing to weaker gravity of the galaxy there. These results in Figs 2–5 clearly demonstrate that moderately strong ram pressure in the IGM can remove halo gas very efficiently, even though it cannot remove the disc gas.

In order to understand more clearly how the disc gas in a disc galaxy can promote or suppress the ram-pressure stripping of the halo gas, we have investigated a comparative model with no disc gas (‘no disc-gas model’, $f_g = 0$). It is found that $F_{\text{strip}}$ in the no disc-gas model is 0.79, which is higher by a factor of 1.2 than that (0.66) in the standard model with disc gas ($f_g = 0.1$). The final distribution of the halo gas in the no disc-gas model is less flattened and a thin gaseous stream behind the disc cannot be seen. These results mean that hydrodynamical interaction between disc and halo gas can suppress ram-pressure stripping of the halo gas.

As shown in Fig. 2, the remaining halo gas at $T = 0.56$ Gyr is compressed and accumulated above the gas disc. About 28 per cent of the remaining halo gas can be located at $X < 0$ (i.e. on the left side of the gas disc) and is likely to be accreted finally on to the disc for further star formation: the low-density gas located at $X > 0$ (i.e. the right side of the disc) is less likely to be accreted rapidly on to the disc. Therefore, the mass fraction of halo gas that can be used for later star formation ($F_d$) after ram-pressure stripping can be significantly smaller than $1 - F_{\text{strip}}$ in disc galaxies ($F_d$ can be typically ~0.3 × $[1 - F_{\text{strip}}]$).

Interestingly, about 0.7 per cent of the halo gas (corresponding roughly to $1.1 \times 10^7$ M$_\odot$) within $R_{\text{halo}}$ can be fuelled to the central 1 kpc of the disc. This radial transfer of halo gas to the central region of the galaxy can be seen in other models with different model parameters. These imply that if the centrally accumulated halo gas can be further transferred to the vicinity of the massive black hole (MBH) located in the centre of the bulge, the halo gas can be used for fuelling the MBH with an accretion rate of ~0.02 M$_\odot$ yr$^{-1}$. These results imply that the ram pressure of the IGM can be responsible for the activation of weak active galactic nuclei (AGN).

### 3.2 Parameter dependences

The dependences of $F_{\text{strip}}$ and the final radial distribution of halo gas are described as follows.

(i) Galactic halo gas can be efficiently stripped from disc galaxies by ram pressure of the IGM in groups with $M_{\text{host}} \approx 10^{13}$ M$_\odot$, though $F_{\text{strip}}$ can be smaller than in cluster models with $M_{\text{host}} \approx 10^{14}$ M$_\odot$. For example, as shown in Fig. 6, the group model with $M_{\text{host}} = 10^{13}$ M$_\odot$ shows $F_{\text{strip}} = 0.38$, which is significantly smaller than

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that (0.66) in the cluster model with $M_{\text{host}} = 10^{13} \, M_\odot$. Fig. 7 clearly shows that the final distribution of halo gas in the group model is less compact and less flattened than that in the cluster model, owing to weaker effects of ram pressure of the IGM in the group model.

(ii) $F_{\text{strip}}$ depends on $M_{\text{host}}$ in such a way that $F_{\text{strip}}$ is higher in models with higher $M_{\text{host}}$. As shown in Fig. 8, the models with $M_{\text{host}} = 10^{13} \, M_\odot$ (corresponding to small groups like the Local Group) do not show any efficient ram-pressure stripping of halo gas. This result suggests that ram-pressure stripping is not so important for galactic global star formation of luminous disc galaxies in small groups with masses of $\sim 10^{12} \, M_\odot$.

(iii) Less massive disc galaxies are likely to lose a larger amount of their halo gas more rapidly for a given environment, though the dependence of $F_{\text{strip}}$ on $M_{\text{gal}}$ is not very strong (see Fig. 8). Fig. 9 clearly shows that even in the group environment with $M_{\text{host}} = 10^{13} \, M_\odot$, less massive galaxies can lose larger mass fractions of their halo gas more rapidly. These results imply that less luminous disc galaxies can truncate their star formation more rapidly after they enter into group and cluster environments.

(iv) For a given $M_{\text{host}}$, $F_{\text{strip}}$ is higher in models with higher $V_r$, owing to a stronger force of ram pressure of the IGM (see Fig. 8). Also, Fig. 10 shows that galactic halo gas can be more rapidly stripped from disc galaxies by ram pressure in models with higher $V_r$. These results suggest that disc galaxies passing through the inner regions of groups and clusters can truncate their star formation more rapidly, owing to more efficient ram-pressure stripping of their halo gas.

(v) $F_{\text{strip}}$ depends on $\rho_{\text{IGM}}$, such that $F_{\text{strip}}$ is higher for models with higher $\rho_{\text{IGM}}$ (see Fig. 8), which is a natural result of $P_{\text{ram}} \propto \rho_{\text{IGM}} \times V_r^2$. It is found that if $\rho_{\text{IGM}} \sim 10^5 \, M_\odot \, \text{kpc}^{-3}$ and $\rho_{\text{IGM}} = 0.1 \, M_\odot \text{kpc}^{-3}$, less massive galaxies can lose larger mass fractions of their halo gas more rapidly, owing to more efficient ram-pressure stripping of their halo gas.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{gas_mass.png}
\caption{The same as Fig. 3 but for the group model.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{final_distributions.png}
\caption{Final distributions of halo (magenta) and disc (cyan) gas projected on to the $x$-$y$ plane for the group model with $M_{\text{host}} = 10^{13} \, M_\odot$ (left) and the cluster model with $M_{\text{host}} = 10^{13} \, M_\odot$ (right). The green solid circle in each frame represents the initial size of the gaseous halo.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{parameter_dependences.png}
\caption{Parameter dependences of $F_{\text{strip}}$ on $V_r$ (upper left), $M_{\text{host}}$ (upper right), $M_{\text{gal}}$ (lower left), and $\rho_{\text{IGM}}$ (lower right). For each parameter dependence, model parameters other than the described one (e.g. $V_r$ in the upper left frame) are set to be the same as those used in the standard model. In the lower right panel, $\rho_{\text{IGM}} \circ$ is the same as the $\rho_{\text{IGM}} (= 10^5 \, M_\odot \, \text{kpc}^{-3})$ used in the standard model.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{gas_mass_time.png}
\caption{The same as Fig. 3 but for four different models with different $M_{\text{gal}}$ in the group model with $M_{\text{host}} = 10^{13} \, M_\odot$: $M_{\text{gal}} = 0.05 \, M_{\odot}$ (solid), $M_{\text{gal}} = 0.1 \, M_{\odot}$ (dotted), $M_{\text{gal}} = 0.5 \, M_{\odot}$ (short-dashed), and $M_{\text{gal}} = 1.0 \, M_{\odot}$ (long-dashed).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{gas_mass_time_vr.png}
\caption{The same as Fig. 3 but for four different models with different $V_r$ in the cluster model with $M_{\text{host}} = 10^{14} \, M_\odot$: $V_r = 500 \, \text{km} \, \text{s}^{-1}$ (solid), $V_r = 1000 \, \text{km} \, \text{s}^{-1}$ (dotted), $V_r = 1500 \, \text{km} \, \text{s}^{-1}$ (short-dashed), and $V_r = 2000 \, \text{km} \, \text{s}^{-1}$ (long-dashed).}
\end{figure}
$V_\odot \sim 400$ km s$^{-1}$ in the small-group model with $M_{\text{host}} = 10^{12}$ M$_\odot$ and $T_{\text{IGM}} = 10^6$ K, then $F_{\text{strip}}$ can be as high as 0.65. This result suggests that the truncation of star formation by ram-pressure stripping of halo gas can be possible even in small and/or compact groups, if their IGM densities are as high as $10^5$ M$_\odot$ kpc$^{-3}$ and member galaxies have moderately larger velocity dispersion ($\sim 400$ km s$^{-1}$).

(iii) $F_{\text{strip}}$ does not depend strongly on $f_g$, $\theta$, $\phi$ and $R_{\text{halo}}$. For example, $F_{\text{strip}}$ can differ only by a factor of $\sim 1.2$ between models with $f_g = 0.01$–0.1. Also, $F_{\text{strip}}$ can differ by a factor of $\sim 1.2$ between models with different $\theta$ and $\phi$. These results imply that the initial distributions of halo and disc gas are less important than other parameters (e.g. $V_\odot$) in determining $F_{\text{strip}}$.

4 DISCUSSION

4.1 Comparison with previous works

Bekki et al. (2002) first investigated how much galactic halo gas can be stripped by ram pressure in groups and clusters of galaxies based on rather idealized numerical simulations. They found that

(i) about 90 per cent of galactic halo gas can be stripped by the combination of tidal and ram-pressure stripping in clusters of galaxies,

(ii) $F_{\text{strip}}$ depends on the orbits of galaxies in groups and clusters, and

(iii) galactic halo gas can be effectively removed from galaxies in groups only if the orbits of the galaxies are rather eccentric.

Although their results can be useful for better understanding the origin of passive spirals, their models are not sophisticated enough to discuss the dependences of $F_{\text{strip}}$ on galaxy environments in a quantitative manner.

Recently, McCarthy et al. (2008) conducted a thorough parameter study on ram-pressure stripping of hot gaseous haloes in galaxies for groups and clusters of galaxies. Their numerical simulations have shown that typically 70 per cent of the initial halo gas around galaxies can be stripped by ram pressure within 10 Gyr in groups and clusters. Although they did not include stellar discs and bulges in their simulations, the result of $F_{\text{strip}}$ is broadly consistent with our simulations ($F_{\text{strip}} \sim 0.6$–0.8), in which cosmologically motivated initial conditions of IGM and halo gas are not adopted. The slight difference in $F_{\text{strip}}$ between their simulations and ours could be due simply to the fact that they did not include disc gas, which is demonstrated to suppress ram-pressure stripping of galactic halo gas in the present study. McCarthy et al. (2008) have also found that $F_{\text{strip}}$ is higher in galaxies with smaller masses for a cluster environment with $M_{\text{host}} = 10^{12}$ M$_\odot$ (i.e. the models with higher mass ratios show higher $F_{\text{strip}}$ in their fig. 8). This is also consistent qualitatively with our results.

Kawata & Mulchaey (2008) have investigated how ram pressure of groups with $M_{\text{host}} = 8 \times 10^{12}$ M$_\odot$ influences gaseous components in disc galaxies with maximum circular velocities of $\sim 150$ km s$^{-1}$ based on cosmological chemodynamical numerical simulations. They have found that ram pressure in a group can be more than enough to remove the hot halo gas of the galaxies, although it cannot remove the cold gas within discs. These results are qualitatively consistent with the present ones, though the initial conditions of disc galaxies in groups are different between Kawata & Mulchaey (2008) and the present study. This consistency implies that the ram pressure of the IGM in groups with $M_{\text{host}} \sim 10^{12}$ M$_\odot$ can play an important role in controlling gas accretion from haloes on to galactic discs and thus determining star formation histories within them.

Although broadly consistent results between the present and previous studies clearly demonstrate that the evolution of hot halo gas around galaxies under ram pressure of the IGM can be one of the key determinants for galaxy evolution, it is not entirely clear how the global properties of galaxies, in particular their morphological, structural and kinematical properties, change after the removal of their halo gas. The present and previous simulations do not enable us to investigate the details of the dynamical properties of disc galaxies after ram-pressure stripping in a fully self-consistent manner. Therefore it is still unclear whether the observed rapid evolution of the S0 fraction in groups (e.g. Wilman et al. 2009) can result from the truncation of star formation in spirals owing to the removal of halo gas in group environments. Given that minor and unequal-mass merging can create S0s (e.g. Bekki 1998), it is important for our future studies to confirm whether the simulated physical properties of S0s formed from spirals through the removal of their halo gas can reproduce the observed ones reasonably well.

4.2 Implications of the present results

4.2.1 Outside-in truncation of star formation

The present study has demonstrated that the outer halo gas can be preferentially stripped from disc galaxies during hydrodynamical interaction between the hot IGM and the halo gas: the remaining gas around discs mostly originates from the inner haloes. This result implies that if the halo gas of a galaxy has an intrinsic angular momentum to be accreted on to the disc, the preferential removal of the outer gas might well result in the suppression of the growth of the outer disc of the galaxy: the inner disc would grow after ram-pressure stripping, though the accretion rate of halo gas would be significantly reduced. Our previous work (Bekki et al. 2002) showed that, after the removal of halo gas, stellar velocity dispersions (and thus the $Q$ parameter) of a disc galaxy can significantly increase in its outer part, owing to dynamical heating of the disc by the spiral arms. The present result combined with our previous one therefore suggests that the gradual truncation of star formation can proceed from the outside in to disc galaxies, owing to more significantly increased $Q$ and reduced $f_g$ (i.e. gas mass fraction) in their outer discs.

This possible outside-in truncation scenario of star formation can provide a clue to the origin of dusty star-forming regions observed in passive spiral galaxies in distant groups and clusters (e.g. Dressler et al. 2009). Recent Spitzer observations of passive spiral galaxies have shown that passive spirals, which were previously suggested to be `dead and red' disc galaxies (Couch et al. 1998), show some levels of star formation (Dressler et al. 2009). The observed dusty star-forming, optically red spirals mean that star-formation activities can be heavily obscured by dust. It is not clear why passive spirals, which should be gas-poor galaxies to explain the observed red colours (i.e. low-level star formation), can show clearly observed star-forming regions (which requires high-density gas and dust). The present outside-in truncation implies that star formation can continue only in the inner high-density regions (after stripping of halo gas), where dust extinction is highly likely to be significant. Thus the outside-in truncation scenario can naturally explain why passive spirals can have dusty star-forming regions without showing star-forming regions not obscured by dust in their outer parts.

Typically $\sim 5$ per cent of the halo gas can be accumulated above gas discs during ram-pressure stripping, and this gas can be strongly
compressed and thus strongly interact hydrodynamically with the
gas discs (see Appendix A for details of the evolution of gas discs
during ram-pressure stripping). As shown in previous numerical
simulations (e.g. Bekki & Couch 2003; Kronberger et al. 2008),
external high-pressure gas may well trigger efficient star formation
in gas discs. Therefore, the present results imply that, before the
gradual truncation of star formation due to ram-pressure stripping of
halo gas in disc galaxies, star formation in galaxies could increase to
some extent. Our future, more sophisticated, simulations including
star formation within giant molecular clouds in disc galaxies under
ram pressure of the IGM will enable us to discuss this problem in a
more quantitative way.

4.2.2 Recycling of ISM

Recent numerical simulations have shown that metal-rich gas
ejected from massive OB stars and supernovae formed during effi-
cient star formation in disc galaxies can be accreted on to the thin
discs, owing to hydrodynamical interaction between the gaseous
ejecta and the gaseous haloes (Bekki, Tsujimoto & Chiba 2009).
This physical mechanism of galactic halo gas keeping gaseous ejecta
within galaxies can work effectively only if the densities of the
gaseous haloes can be as high as $10^{-5}$ cm$^{-3}$ (Bekki et al. 2009).
These results, combined with the present ones, therefore suggest
that if galaxies enter inter-group and cluster environments and lose
most of their halo gas owing to ram-pressure stripping, then the
recycling processes of metal-rich gaseous ejecta in the interstellar
medium (ISM) of galaxies can be dramatically changed, owing to
gaseous haloes with much lower densities.

If recycling processes of the metal-enriched ISM can be severely
suppressed by ram-pressure stripping of galactic halo gas, then
chemical evolution of disc galaxies after the stripping can also be
significantly changed. For example, energetic stellar winds from
supernovae and massive OB stars in luminous disc galaxies under
the influence of ram pressure can easily escape from the galaxies and
be dispersed into the IGM of their host environments. Less energetic
winds, like those from AGB stars, on the other hand, can still be
trapped within the galaxies so that their ejecta can be used for further
star formation and thus for chemical evolution. As a result of these,
abundance patterns might well be significantly different between
field disc galaxies, which can retain gaseous ejecta both from AGB
stars and supernovae well, and cluster/group disc galaxies, which
can retain only AGB ejecta. Our future quantitative investigation on
the chemical evolution of disc galaxies after ram-pressure stripping
of their halo gas will enable us to address the important question as
to how the abundance patterns in discs are different between field
and group/cluster disc galaxies.

5 CONCLUSIONS

We have investigated the time-evolution of galactic halo gas in
disc galaxies under moderately strong ram pressure of the IGM
in different environments based on self-consistent hydrodynamical
simulations with various different model parameters. We summarize
our principle results as follows.

(1) Even moderately strong ram pressure of the IGM with $\rho_{\text{IGM}} \approx 10^3$ M$_{\odot}$ kpc$^{-3}$ and $V_1 \approx 500$ km s$^{-1}$ can strip galactic halo gas efficiently in clusters of galaxies with $M_{\text{host}} = 10^{14}$ M$_{\odot}$. Typically 60–80 per cent of initial halo gas can be stripped from disc galaxies (i.e. $F_{\text{strip}} = 0.6 = 0.8$) in clusters, which is broadly consistent with the results of other studies.

(2) $F_{\text{strip}}$ depends on $M_{\text{host}}$, such that it can be higher in environ-
ments with higher $M_{\text{host}}$. For example, $F_{\text{strip}}$ can be as large as 0.4
in group environments with $M_{\text{host}} = 10^{13}$ M$_{\odot}$. $F_{\text{strip}}$ in small and comp-
act groups with low IGM temperature ($T_{\text{IGM}} = 10^5$ K) can be as
large as ~0.6, if the groups have IGM with $\rho_{\text{IGM}} \approx 10^5$ M$_{\odot}$ kpc$^{-3}$
and $V_1 \approx 400$ km s$^{-1}$. These results imply that strangulation can
happen even in small and/or compact groups with higher velocity
dispersions.

(3) The presence of disc gas in disc galaxies can suppress the
ram-pressure stripping of their halo gas owing to hydrodynamical
interaction between halo and disc gas. This result suggests that the
stripping processes of halo gas by ram pressure can be significantly
different between late- and early-type galaxies with and without
disc gas.

(4) Disc galaxies with lower masses ($M_{\text{gal}}$) are likely to show appreciably higher $F_{\text{strip}}$ in a given environment. This result implies
that strangulation can proceed more rapidly and more efficiently
in disc galaxies with lower $M_{\text{gal}}$. The remaining halo gas of disc
galaxies after ram-pressure stripping shows more compact and flat-
tened distributions and has jellyfish-like configurations, irrespective
of $M_{\text{gal}}$.

(5) Most halo gas stripped by ram pressure in disc galaxies can
originate from the outer parts of the haloes, so that only halo gas
initially in the inner parts can be accreted on to the discs during/after
ram-pressure stripping. This suggests that strangulation is more effi-
cient in the outer discs and thus that the truncation of star formation
by stripping of the halo gas may well proceed from the outside in
disc galaxies. This outside-in truncation can provide a clue to the
origin of red passive spirals in distant groups and clusters.

(6) Ram-pressure stripping of galactic halo gas is much more
efficient than that of disc gas in groups and clusters, and efficiencies
of halo- and disc-gas stripping can be different in different environ-
ments with different $M_{\text{host}}$, $V_1$ and $\rho_{\text{IGM}}$. The mass ratios of halo
gas to disc gas in disc galaxies can reflect the environments in which
they have resided during their histories and thus be significantly
different between disc galaxies.

(7) It is suggested that recycling processes of the ISM and the
chemical evolution of galaxies significantly change after the re-
moval of galactic halo gas. One example is that gaseous ejecta from
energetic massive OB stars and supernovae can more easily escape
from disc galaxies after halo-gas stripping, owing to much less effec-
tive hydrodynamical interaction between the gaseous ejecta and halo
gas. Abundance patterns of the ISM in disc galaxies are thus sug-
gested to be significantly different between different environments.

(8) Small fractions of the halo gas (0.3–1 per cent) in disc galaxies
can be accumulated into the central 1 kpc of galactic bulges owing
to the compression of halo gas during ram-pressure stripping. This
gas can be used for fuelling the central MBH and activating a weak
AGN there, though the final dynamical fate of the accumulated halo
gas is beyond the scope of this paper.

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APPENDIX A: PHYSICAL PROPERTIES OF GAS DISCS DURING RAM-PRESSURE STRIPPING

Fig. A1 shows the time-evolution of the morphological properties of the gas disc for the last 0.56 Gyr in the standard model. As the halo gas is compressed by the strong ram pressure of the IGM, hydrodynamical interaction between disc and halo gas becomes stronger (T = 0.21 Gyr). Gaseous spiral arms can be developed in the inner region of the disc during ram-pressure stripping, though the outer part of the gas disc can lose a minor fraction of its initial gas (T = 0.28 Gyr). The final morphology of the gas disc appears to be more compact (T = 0.56 Gyr), owing to compression of the gas disc by the halo gas and IGM.

Fig. A2 shows the number distributions of pressure of disc-gas particles (P ) at T = 0.21 Gyr and T = 0.56 Gyr in the standard model. The mean P values at T = 0.21 Gyr and T = 0.56 Gyr are 1.1 × 10^{-11} \text{ dyn cm}^{-2} and 1.3 × 10^{-11} \text{ dyn cm}^{-2}, respectively (i.e. the mean log_{10}P at T = 0.21 Gyr and T = 0.56 Gyr is −10.94 and −10.88, respectively). Although the mean pressure is not so different between the two time-steps, the mass fraction of disc-gas particles that have pressure higher than 5 × 10^{-11} \text{ dyn cm}^{-2} (f_{\text{thres}}) is significantly different: f_{\text{thres}} = 0.04 at T = 0.21 Gyr and 0.09 at T = 0.56 Gyr. This reflects the fact that as time passes, the
disc-gas particles feel stronger pressure from the halo gas (and IGM) owing to the more strongly compressed halo gas.

Recently Kapferer et al. (2009) have shown that if the pressure of the IGM is as high as $5 \times 10^{-11}$ dyne cm$^{-2}$, ram pressure can significantly enhance star formation in disc galaxies, owing to the compression of disc gas by ram-pressure force. Our results in Fig. A2 therefore imply that star formation can be enhanced for some minor fraction ($<10$ per cent) of disc gas during ram-pressure stripping. Although numerical models $P$ in Kapferer et al. (2009) and in the present study are different, our results in Fig. A2 confirm the early suggestion (e.g. Bekki & Couch 2003; Kronberger et al. 2008) that ram pressure can trigger the formation of new stars in gas discs. Numerical results by Kronberger et al. (2008) and from the present study are consistent with each other in that they show more efficient stripping of disc gas in the outer parts of gas discs: star formation might well be truncated from the outside in.

APPENDIX B: DESCRIPTION OF THE ANIMATION

We have made a simple animation for the time-evolution of the mass distributions of halo and disc gas projected on to the $x$–$z$ plane for the standard model. Only halo and gas particles are shown, by magenta and cyan respectively, for clarity: the dark matter halo, stellar disc and bulge and hot IGM are not shown. The model parameters for the standard model are described in detail in the main text.

Hot gas particles for the IGM are initially placed on equally spaced grids so that the adopted uniform density distribution of the IGM can be achieved in the present study. In the early phase of ram-pressure stripping of galactic halo gas by the IGM, some grid-like local structures can be seen owing to (i) the adopted IGM distribution and (ii) the small number of IGM particles. Since these local structures soon disappear, the final mass and distributions of galactic halo gas after ram-pressure stripping, which are the main focus of the present paper, cannot be influenced significantly by the development of such structures (which is due to the adopted numerical models for the IGM). The animation is available with the online version of the paper – see Supporting Information.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix B. Animation for the time-evolution of the mass distributions of halo and disc gas projected on to the $x$–$z$ plane for the standard model. The format of this animation is AVI.

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