Ram pressure stripping in a viscous intracluster medium

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ABSTRACT

In the recent literature, there is circumstantial evidence that the viscosity of the intracluster medium (ICM) may not be too far from the Spitzer value. In this Letter, we present two-dimensional hydrodynamical simulations of ram pressure stripping of disc galaxies in a viscous ICM. The values of viscosity explored range between 0.1 and 1.0 times the Spitzer value. We find that viscosity affects the appearance and the dimensions of the galactic wakes but has very little effect on the evolution of the gas mass of the galaxy.

Key words: galaxies: evolution – galaxies: individual: NGC 4388 – intergalactic medium – galaxies: ISM – galaxies: spiral.

1 INTRODUCTION

In clusters, galaxies can lose some or all of their gas by ram pressure stripping (RPS) due to their motion through the intracluster medium (ICM). Both, analytical estimates (Gunn & Gott 1972) and (hydro)dynamical simulations (e.g. Abadi, Moore & Bower 1999; Quilis & Moore 2001; Schulz & Struck 2001; Vollmer et al. 2001a; Marcolini, Brighenti & A.D’Ercole 2003; Roediger & Brüggen 2006, 2007) show that RPS can remove a significant amount of gas from galaxies, and is thus important for the evolution of galaxies and the ICM.

In addition to gas loss by ram pressure pushing, galaxies also suffer gas loss by continuous (sometimes also called turbulent or viscous) stripping (e.g. Nulsen 1982; Quilis, Moore & Bower 2000; Schulz & Struck 2001; Roediger & Hensler 2005; Roediger & Brüggen 2006).

Nulsen (1982) has studied the effects of transport processes and turbulence on the flow of gas past a galaxy and has found that they could produce more stripping of gas than ram pressure alone. For turbulent stripping, he found a mass stripping rate of

\[ M_{\text{turb}} \sim \pi r^2 \rho_{\text{ICM}} v \sim 7 r_\odot^2 n_{\text{H}} v_{\text{turb}} M_{\odot} \text{yr}^{-1}, \tag{1} \]

where \( r = 10 r_\odot \) kpc, \( \rho_{\text{ICM}} = 10^{-3} n_{\text{H}} \text{M}_\odot \text{cm}^{-3} \) and \( v = 1000 v_{\text{turb}} \text{km s}^{-1} \). This is similar to what is found in the simulations by Roediger & Brüggen (2006) and Roediger & Brüggen (2007) who find rates of about \( \sim 10^{-3} M_{\odot} \text{yr}^{-1} \). Turbulent stripping is mainly caused by the Kelvin–Helmholtz instability, which is suppressed by viscosity that stabilizes modes with wavelengths smaller than \( r/Re \) (e.g. Betchov & Criminale 1967).

There exist only few detailed studies on the wakes of stripped galaxies. Using the hydrodynamical adaptive mesh-refinement code FLASH, we have studied galactic ram pressure tails in a constant ICM wind (Roediger, Brüggen & Hoeft 2006) as well as for galaxies on realistic cluster orbits (Roediger & Brüggen 2008). The minimum tail width of about 20 to 30 kpc is found near the galaxy. With increasing distance to the galaxy, the tail flares to widths of 30 to 80 kpc at a distance of \( \sim 100 \text{kpc} \) behind the galaxy. Other hydrodynamical simulations using either grid codes (e.g. Quilis & Moore 2001; Marcolini et al. 2003) or smoothed particle hydrodynamics (e.g. Abadi et al. 1999; Schulz & Struck 2001) do not focus on the tails. However, according to the snapshots provided in these papers, the gas tails are similar to the ones in our simulations. Using a sticky-particle code, Vollmer et al. (e.g. Vollmer et al. 1999, 2000, 2001a,b; Vollmer 2003; Vollmer et al. 2004; Vollmer, Huchtmeier & van Driel 2005; Vollmer et al. 2006) aim at reproducing the RPS history of individual galaxies by comparing simulations and observations. However, these simulations concentrate on the gas distribution close to the galaxy.

Recently, Oosterloo & van Gorkom (2005) presented observations of a \( \sim 120 \text{kpc} \) long and \(< 25 \text{kpc} \) wide tail of H I gas associated with NGC 4388, and also suggest that this tail is due to ram pressure stripping of this galaxy, either in the ICM of the Virgo cluster or in the halo of the nearby elliptical galaxy M86. However, the tail of NGC 4388 is narrower than the tails in the simulations presented in Roediger & Brüggen (2006) and Roediger & Brüggen (2008), although it seems to be flaring in a similar fashion as found in the simulation. Also the X-ray and Hα tails observed by Sun et al. (2006); Sun, Donahue & Voit (2007) and Yagi et al. (2007) are much narrower than simulated ram pressure tails: while being only \( \sim 7 \text{kpc} \) wide, they reach lengths of \( \sim 70 \text{kpc} \) and show hardly any flaring. This difference may be caused by the microphysics of the ICM.

The viscosity of the ICM has been discussed before. Based on the observations of the Perseus cluster, it has been suggested by Fabian et al. (2003a) and Fabian et al. (2003b) that viscosity may play an important role in dissipating energy injected by the central active galactic nuclei. Circumstantial evidence for the presence of significant ICM viscosity is also provided by an examination of the morphology of Hα filaments in the Perseus cluster. Several of the filaments appear to trace well-defined arcs which argues

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against the presence of strong turbulence in the ICM core, possibly resulting from the action of viscosity. This idea has been tested in numerical simulations by Ruszkowski, Brueggen & Begelman (2004a,b) and Reynolds et al. (2005).

In the case of a fully ionized and unmagnetized, thermal plasma, the relevant coefficient of viscosity is given by Braginskii (1958) and Spitzer (1962) as \( \mu = 6.0 \times 10^{-17} (\ln A/37)^{-1} T^{5/2} g \text{ cm}^{-1} \text{ s}^{-1} \), where \( T \) is the temperature of the plasma measured in Kelvin and \( \ln A \) is the Coulomb logarithm. It results from the cumulative effect of weak Coulomb collisions. The mean-free path of such interactions scales with \( T^2 \). As the sound-speed scales with \( T^{3/2} \), the viscosity is proportional to \( T^{3/2} \).

It is customary to measure the importance of viscosity through the Reynolds number, \( Re = v l / \nu \), where \( v \) and \( l \) are velocities and length-scales of the system and \( \nu = \mu / \rho \) the kinematic viscosity, with \( \rho \) being the fluid density. For our case

\[
\text{Re} \sim 26 \nu_R \rho_{ICM}^{-1} f_v^{-1} \left( \frac{kT}{5 \text{ keV}} \right)^{-2.4},
\tag{2}
\]

which indicates that viscosity may play a role unless the viscosity is strongly suppressed, i.e. the suppression factor, \( f_v \), is sufficiently small.

This suppression results from the cluster magnetic fields. Even weak fields lead to a tiny proton gyroradius, which results in a very efficient suppression (a factor of \( \sim 10^{23} \) for typical ICM conditions, Spitzer 1962) of the local viscosity perpendicular to the magnetic field. Magnetic fields in the ICM are certainly tangled or even chaotic (Clarke 2004; Enßlin, Vogt & Pfremmer 2005) and will lead to a reduced macroscopic viscosity. The degree of reduction, however, is unknown. Due to the same mechanism, also thermal conduction in the ICM is suppressed perpendicular to the magnetic field lines. In a recent study, Narayan & Medvedev (2001) found an effective macroscopic thermal conductivity that is a factor of \( f_v \sim 10^{-2} \) –0.2 lower than the unmagnetized value. Similar arguments may apply to the viscosity. From studies of ICM turbulence in the Coma cluster, Schuecker et al. (2004) derive an upper limit on the kinematic viscosity of the ICM of \( \sim 3 \times 10^{19} \text{ cm}^2 \text{ s}^{-1} \). For typical ICM densities and temperatures, this corresponds to a viscosity suppression factor of \( f_v \) around 0.1. Thus, we might expect the viscosity to be suppressed by some factor between \( 10^{-2} \) and unity.

The magnetic fields of the ICM (e.g. Clarke 2004; Enßlin et al. 2005) may themselves influence the appearance of ram pressure stripped galaxies. Given that the thermal pressure in the ICM dominates over the magnetic pressure, the magnetic fields should be frozen-in and follow the ICM flow. Thus, they should be generally parallel to the galaxy’s tail. Such a magnetic field structure could attenuate thermal conduction between the stripped gas and the hot ICM, and it could suppress, for example, Kelvin–Helmholtz and maybe even Rayleigh–Taylor instabilities in the tail. However, it is unclear how well the magnetic fields will be aligned with the ICM–ISM interfaces and how strong this suppression will be. The influence of the magnetic fields will be studied in a forthcoming paper.

Here, using adaptive mesh, hydrodynamical simulations, we investigate the effect of a macroscopic viscosity on the stripping of gas from a galaxy.

## 2 METHOD

We model the ICM–ISM interaction in the galaxy’s rest frame, i.e. the galaxy is exposed to an ICM flow. The work of Roediger & Brüggen (2007) showed that the classical estimate of the stripping radius given by Gunn & Gott (1972) can be adapted to galaxies exposed to a variable ICM wind. Therefore, here we decouple the effect of time-variability and use a constant ICM wind to focus on the effect of viscosity.

To include viscosity in our hydrosimulations, we add velocity diffusion to the momentum equation:

\[
\frac{\partial (\rho v_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho v_i v_j) + \frac{\partial P}{\partial x_i} = \rho g_i + \frac{\partial \pi_k}{\partial x_i},
\tag{3}
\]

with

\[
\pi_k = \frac{\partial}{\partial x_i} \left[ 2 \mu \left( e_k - \frac{1}{3} \Delta \delta_k \right) \right],
\tag{4}
\]

where \( P \) is pressure, \( \rho \) is density, \( v_i \) is the components of velocity, \( g_i \) is the components of the gravitational acceleration and \( \Delta = \delta_i \). Here, \( \mu \) is the coefficient of (shear) viscosity. In our simulations, we neglected bulk viscosity since it vanishes for an ideal gas. We use the standard Spitzer viscosity for an unmagnetized plasma, for which \( \mu = 6.0 \times 10^{-17} (\ln A/37)^{-1} T^{5/2} g \text{ cm}^{-1} \text{ s}^{-1} \).

We have noted earlier that the precise value of the suppression factor is highly uncertain and, depending on the nature of magnetic turbulence, may even exceed the Spitzer value (Cho, Lazarian & Vishniac 2003) or be suppressed well below it. For our viscous simulations, we choose \( f_v \) between 0 and 1 (see Table 1).

In order to ensure numerical stability and to prevent too small time-steps, we have switched off viscosity for temperatures outside the range \( 3 \times 10^5 < T < 1.5 \times 10^8 \text{ K} \). The total energy fluxes are not modified by viscosity as the effects of viscous heating are small.

### 2.1 Code

The simulations were performed with the FLASH code (Fryxell et al. 2000) version 2.5, a multidimensional adaptive mesh-refinement hydrodynamics code. It solves the Riemann problem on a Cartesian grid using the piecewise-parabolic method (PPM).

The viscous runs are fairly expensive because the time-step imposed by the viscosity scales as \((\Delta x)^2/\mu\), where \( \Delta x \) is the resolution of the computational grid. As this time-step scales more strongly with \( \Delta x \) than the standard hydrodynamical Courant condition, and because viscosity depends strongly on temperature, the constraints on the time-step are more stringent than in the inviscid runs. Hence, here we present only results from two-dimensional simulations in cylindrical coordinates, \((R, Z)\).

The ICM wind enters the simulation box at \( Z = -65 \text{ kpc} \). The boundary at \( R = 0 \) is the galaxy’s symmetry axis, the remaining two

| Run: | M08 | M08–V1 | M08–V2 | M08–V3 |
|------|-----|--------|--------|--------|
| \( \rho_{ICM}/10^{-27} \text{ g cm}^{-3} \) | 1   | 1      | 1      | 1      |
| \( v_{ICM}/1000 \text{ km s}^{-1} \) | 0.8 | 0.8    | 0.8    | 0.8    |

| Run: | M20 | M20–V |
|------|-----|-------|
| \( \rho_{ICM}/10^{-27} \text{ g cm}^{-3} \) | 1   | 1     |
| \( v_{ICM}/1000 \text{ km s}^{-1} \) | 2   | 2     |
| \( f_v \) | 0.1 |       |
boundaries obey outflow conditions. We use a grid size of 260 kpc in Z-direction 65 kpc in R-direction. With five refinement levels, we reach an effective number of 2048 × 256 grid cells and effective resolution of 0.25 kpc.

2.2 Model galaxy

The galaxy model is the same as in Roediger & Brüggen (2006), i.e. a massive spiral with a flat rotation curve at 200 km s\(^{-1}\). It consists of a dark matter halo (1.1 × 10\(^{11}\) M\(_{\odot}\) within 23 kpc), a stellar bulge (10\(^{10}\) M\(_{\odot}\)), a stellar disc (10\(^{11}\) M\(_{\odot}\)) and a gaseous disc (5 × 10\(^{9}\) M\(_{\odot}\)). All non-gaseous components just provide the galaxy’s potential and are not evolved during the simulation. For a description of the individual components and a list of parameters please refer to RB06. Initially, the gas disc is set in hydrostatic equilibrium with the surrounding ICM (see also RB06). The disc’s rotation is included via the centrifugal force.

2.3 ICM conditions

Table 1 lists the ICM conditions for the simulation runs. The ICM temperature was 7.2 × 10\(^{7}\) K or 6.2 keV in all runs.

We start the simulation with the ICM at rest and then increase the inflow velocity over the first 50 Myr from zero to \(v_{\text{ICM}}\) (for more details see RB06).

3 RESULTS

Fig. 1 shows the density in the subsonic runs with increasing viscosity: \(f_v = 0, 0.1\) and 0.5. The different behaviour of the galactic wakes is evident: the larger the viscosity, the less turbulent the wake. In the viscous cases, the ICM flows past the galaxy more smoothly than in the non-viscous runs. In the non-viscous cases, the KH and RT instabilities cause vortices and turbulence. Both instabilities are suppressed significantly in the viscous cases. Consequently, the stripped gas remains in larger clumps and is less readily mixed with the ambient medium.

Also the width of the tail, or the flaring angle, is slightly smaller in the viscous runs. In the inviscid run, the maximum width of the tail is \(\approx 2 \times 40\) kpc, while it is \(\approx 2 \times 35\) kpc in all viscous runs. Thus, it is also unlikely that the small width of the tail in NGC 4388 and the X-ray tails of ESO137–001 (Sun et al. 2006) can be explained by a microphysical, Spitzer-type viscosity. Interestingly, the tail appears to be shorter, the larger the viscosity. This is due to the fact that larger gas clouds, even if they have the same density like smaller clouds, experience a smaller acceleration for a fixed ram pressure. We note that the mass fraction of stripped gas in dense form does not depend strongly on viscosity. In the viscous cases, there are a few large dense clouds, whereas in the non-viscous case there are numerous small dense clouds. We do not show any plots here for the supersonic runs but they show the same qualitative behaviour.

Fig. 2 compares the evolution of the mass and radius of the remaining gas disc for viscous and inviscid runs. The top panel demonstrates that the viscosity has nearly no influence on the evolution of the gas disc’s radius. The bottom panel displays the gas mass in a cylinder of radius 27 kpc and a height of 10 kpc. Interestingly, the mass evolution in all runs is very similar, for all values of the viscosity that we have explored. The first dip in the graph marks the end of the instantaneous stripping phase. Very slight differences
introduced by the viscosity occur during the next, the intermediate phase and also during the final continuous stripping phase. We have also measured the gas mass bound to the gravitational potential of the galaxy and its behaviour is shown in the middle panel of Fig. 2. The differences between runs with and without viscosity are similar to that of the gas disc mass. This implies that the amount of gas lost from the galaxy is fixed by the ram pressure.

This result shows that the viscosity in the parameter range considered here has a minor impact on the mass-loss history of the gas disc and that ram pressure pushing is the dominant mechanism, as found in earlier papers (e.g. Roediger & Brüggen 2006, 2007). The fact that the viscosity has a minor impact on the mass-loss history should also hold for most galaxies which move through clusters and thus experience a variable ram pressure – for the very reason that the viscosity has a minor impact on the mass-loss history of the gas disc and that ram pressure pushing is the main cause for mass-loss also for these galaxies (Roediger & Brüggen 2007). The mass loss due to ram pressure pushing, i.e. during the first, instantaneous stripping phase, is especially insensitive to different ICM viscosities. An exception may occur when galaxies move near edge-on.

4 DISCUSSION

Clearly, we have to be careful with quantitative predictions especially concerning the morphology of the wake because our simulations are two-dimensional. However, in previous work we have shown that mass-loss rates are the same in two-dimensional and three-dimensional simulations. Moreover, in the non-viscous cases, the wake structures in two-dimensional and three-dimensional were very similar. Thus, our main conclusions should be robust.

(i) The mass-loss from the gas discs is hardly influenced by viscosity.
(ii) With increasing viscosity, the wake shows less structure and turbulence, but larger clumps.

A detailed investigation of the fate of the stripped gas requires several additions to our simplified model: a three-dimensional treatment to allow for other inclinations than face-on, prescriptions for heating, cooling and thermal conduction. These processes do not only influence the temperature in the stripped gas, but also determine in which wavebands the stripped gas will be observable. For the fate of the stripped gas, viscosity may make a difference as it may affect the thermal history of the stripped gas. Gradients of density and temperature are smeared out in the wake in the presence of viscosity. This will affect the efficiency of heat conduction and evaporation of clumps in the galactic wakes. It will also affect the efficiency with which material in the wake can form stars as observed by Sun et al. (2007). Comparisons between models and observations will reveal which processes are the dominant ones in shaping galactic tails.

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