Influence of AGN Outbursts on the Surrounding Galaxies

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ABSTRACT

We study the influence of a strong AGN outburst on the surrounding galaxies. The AGN is assumed to reside in a group of galaxies, and an outburst excites a shock wave in the hot gas in the group. We calculate the impact of the shock wave on the galaxies. We find that if the energy of the outburst is extremely large ($E_{\text{AGN}} \sim 6 \times 10^{61} \text{ erg}$) as the one recently observed in clusters, the impact is strong enough to strip the cold interstellar medium in the disc of the galaxies in the inner region of the group. Moreover, even in the outer region of the group, the warm gas in the halo of the galaxies would be stripped, even if the energy of the outburst is $\sim 6 \times 10^{60} \text{ erg}$. These would decrease star formation activity of the galaxies. If these galaxies fall into the group centre through dynamical friction and their interstellar medium is the fuel of the supermassive black hole in the AGN, the outburst would serve as feedback. While this mechanism works only when $E_{\text{AGN}}$ is extremely large, such outbursts have not been observed in groups at low redshift; it would work at high redshift rather than at low redshift.

Key words: galaxies: active – galaxies: clusters: general – galaxies: interactions – galaxies: intergalactic medium.

1 INTRODUCTION

X-ray observations have shown that hot gas in groups and clusters of galaxies has been heated by some sources in addition to gravity. This was shown by the fact that the luminosity and temperature of a group or cluster follow a scaling relationship (the $L_X-T$ relation), $L_X \propto T^2$ (Edge & Stewart 1991; Allen & Fabian 1998; Markevitch 1998; Arnaud & Evrard 1999), which is at odds with that expected for groups and clusters formed by gravitational structure formation, with $L_X \propto T^2$ (Kaiser 1986). More recently, it was shown that the entropies of the hot gas in groups and clusters, especially groups, are higher than those predicted by models of gravitational structure formation (Ponman, Cannon, & Navarro 1999).

Supernova-driven galactic winds have been considered as the heating source (Wu, Fabian, & Nulsen 1998; Menci & Cavaliere 2000; Loewenstein 2000). However, the energy from supernovae alone seems to be insufficient to heat the hot gas to the observed level (Valageas & Silk 1999; Wu, Fabian, & Nulsen 2000; Bower et al. 2001). Therefore, active galactic nuclei (AGNs) are now recognised as another promising candidate of the heating source (Inoue & Sasaki 2001).

AGNs are often found at the centres of groups and clusters (McNamara et al. 2004; Fabian et al. 2004; Blanton et al. 2001). The energy ejected by an AGN can cancel radiative cooling of the hot gas and may prevent development of a cooling flow in the central region of a group or a cluster. For most of the AGNs at $z \sim 0$, however, the power is not enough to heat the hot gas on a group or cluster-scale, and would be insufficient to account for the entropy excess found in groups and clusters. Recently, however, shock waves associated with extremely powerful AGN outbursts have been found in some clusters (McNamara et al. 2005; Nulsen et al. 2005a,b; Wise et al. 2007; Gitti et al. 2007). They seem to be powerful enough to heat the gas on a group or cluster-scale.

Such strong outbursts would also affect the surrounding environment in a form other than heating. For example, Fujita et al. (2007) showed that the shock wave excited by an outburst accelerates particles and that the emission from the accelerated particles could be responsible for radio mini-halos observed in clusters. Rawlings & Jarvis (2004) discussed the regulation of galaxy formation by outbursts.

In this letter, we consider another effect of strong AGN outbursts on the environment. We focus on the interaction between the shock wave produced by an outburst and the galaxies surrounding the AGN. We consider an AGN and galaxies in a small group of galaxies with the mass of $10^{13} M_\odot$ rather than a cluster of galaxies. In clusters, another interaction between the hot gas and the galaxies, called ram-
pressure stripping, is effective (see Section 4). Thus, the influence of AGN outbursts would be obscured.

It should be noted that such strong outbursts are rare phenomena at low redshift. Gitti et al. (2007) estimated that strong outbursts (\(E_{\text{AGN}} \approx 10^{45}\) erg) are likely to occur only \(\sim 10\%\) of clusters at low redshift. For groups, the fraction may even be smaller because such outbursts have not been observed. However, at high redshift, they would be more common (Ueda et al. 2003, see Section 4). In this letter, the cosmological parameters are \(\Omega_0 = 0.3, \lambda_0 = 0.7,\) and \(h = 0.7,\) where \(H_0 = 100\) h km s\(^{-1}\) Mpc\(^{-1}\).

2 MODELS

2.1 Dark Matter and Gas Profile

Using one-dimensional hydrodynamic simulations, we estimate the impact of the shock wave created by an AGN outburst on galaxies. We assume that an AGN is located at the centre of a group of galaxies with the virial mass of \(M_{\text{vir}}\) and that the group is spherically symmetric. For the mass distribution of the group, we adopt the so-called NFW profile (Navarro, Frenk, & White 1997), although later studies indicated that the central cusp would be steeper (e.g. Fukushige & Makino 1997). The mass profile is written as

\[
M(R) \propto \left[ \ln \left(1 + \frac{R}{R_s}\right) - \frac{R}{R_s(1 + R/R_s)} \right],
\]

where \(R_s\) is the characteristic radius of the group. The normalisation can be given by \(M(R_{\text{vir}}) = M_{\text{vir}}\), where \(R_{\text{vir}}\) is the virial radius of the group.

The virial radius is given by

\[
R_{\text{vir}} = \left[ \frac{3M_{\text{vir}}}{4\pi\Delta_c(z)\rho_\odot(z)} \right]^{1/3},
\]

where \(\Delta_c(z)\) is a spherical over-density of the virialized dark halo within \(R_{\text{vir}}\) at redshift \(z\), in units of the critical density of the Universe at \(z\), or \(\rho_\odot(z)\). For \(\Delta_c(z)\), we use the fitting formula of Bryan & Norman (1998) for a flat Universe with a non-zero cosmological constant, \(\Delta_c(z) = 18\pi^2 + 82x - 39x^2\), where \(x = \Omega(z) - 1\) and \(\Omega(z)\) is the cosmological density parameter at redshift \(z\). The concentration parameter of the group, \(c_{\text{vir}} = R_{\text{vir}}/R_s\), is given by

\[
c_{\text{vir}} = \left( \frac{9}{1 + z^2} \left[ \frac{M_{\text{vir}}}{1.5 \times 10^{15}h^{-1}M_\odot} \right]^{-0.13} \right)^{-1/3}.
\]

(Bullock et al. 2001).

Initially, hot gas or intragroup medium (IGM) is in pressure equilibrium with the gravitational potential formed by the group. We assume that the initial IGM density and temperature profiles follow the ‘universal profile’ derived by Komatsu & Seljak (2001). They can respectively be written as

\[
\rho_{\text{IGM}}(R) = \rho_{\text{IGM}}(0)\gamma_{\text{IGM}}(R/R_s),
\]

\[
T_{\text{IGM}}(r) = T_{\text{IGM}}(0)\gamma_{\text{IGM}}^{-1}(R/R_s),
\]

where

\[
\gamma_{\text{IGM}}(x) = \left[ \frac{\gamma' - 1}{\gamma' - 1} \right] \left[ 1 - \frac{\ln(1 + x)}{x} \right],
\]

\[
m(x) = \ln(1 + x) - x/(1 + x).
\]

The parameters \(\gamma_0\) and \(\gamma'\) can be derived from the condition that the IGM and dark matter profiles are the same in the outermost region of the group (Komatsu & Seljak 2001).

We solve the following equations:

\[
\frac{\partial \rho_{\text{IGM}}}{\partial t} + \frac{1}{R^2} \frac{\partial}{\partial R} \left( R^2 \rho_{\text{IGM}} V_{\text{IGM}} \right) = 0,
\]

\[
\frac{\partial (\rho_{\text{IGM}}V_{\text{IGM}})}{\partial t} + \frac{1}{R^2} \frac{\partial}{\partial R} \left( R^2 \rho_{\text{IGM}} V_{\text{IGM}}^2 \right) = - \rho_{\text{IGM}} GM(R) - \frac{\partial p}{\partial R},
\]

where \(G\) is the gravitational constant, and \(p\) and \(V_{\text{IGM}}\) are the pressure and velocity of the IGM, respectively. The total energy is defined as \(\epsilon = \rho_0 \gamma_{\text{IGM}} V_{\text{IGM}}^2/2\), where \(\gamma = 5/3\). Although we include the cooling function \(\Lambda(T_{\text{IGM}})\), the evolution of the shock is faster than the radiative cooling.

\[\text{Electron density is defined as } n_e = 0.86 \rho_{\text{IGM}}/m_p,\text{ where } m_p\text{ is the proton mass.}\]

We ignore the self-gravity of IGM.

2.2 The Criterion for Stripping

The cold interstellar medium (ISM) in the disc of a galaxy would be stripped when a shock wave excited in the IGM passes the galaxy. Since the shock wave passes the galaxy in a short time (less than the dynamical time or the rotation time of the galaxy), momentum transfer causes stripping to occur. The integrated momentum from the IGM per unit area at radius \(R\) is

\[
s(t, R) = \int_0^t \rho_{\text{IGM}}(t, R)V_{\text{IGM}}^2(t, R)dt.
\]

Thus, the criterion of stripping for a galaxy at radius \(R\) is

\[
s(t, R) > \Sigma_{\text{ISM}}v_{\text{esc}},
\]

where \(\Sigma_{\text{ISM}}\) is the column density of the cold ISM in the galactic disc, and \(v_{\text{esc}}\) is the escape velocity of the galaxy. Strictly speaking, this relation is valid only when the galaxy is face-on; if not, the stripping would be less efficient. In this relation, we assume that the galaxy is not moving relative to the group. The AGN explodes at \(t = 0\).

The escape velocity is given by \(v_{\text{esc}} \sim \sqrt{2} v_{\text{rot}},\) where \(v_{\text{rot}}\) is the rotation velocity of the galaxy. (The ISM may stay in the halo of the galaxy with this velocity.) Mo, Mao, & White (1998) indicated that for a given \(v_{\text{rot}}\) the total disc surface density of a galaxy, \(\Sigma_\star\), is proportional to the Hubble constant at redshift \(z\):

\[
H(z) = H_0[1 + (1 - \lambda_0 - \Omega_0)(1 + z)^2 + \Omega_0(1 + z)^3]^{1/2}.
\]

Following Fujita & Goto (2004), we assume that the ISM column density is proportional to the disc surface density (\(\Sigma_{\text{ISM}} \propto \Sigma_\star\)). Thus, the former is given by

\[
\Sigma_{\text{ISM}}(z) = \Sigma_{\text{ISM}}(0)H(z)/H_0.
\]

Moreover, we assume that the disc radius of a galaxy has a relation of
\[ r_{\text{gal}}(z) = r_{\text{gal}}(0)[H(z)/H_0]^{-1} \]

(Mo et al. [1998].)

3 RESULTS

We consider the influence on galaxies in groups exerted by an extremely strong AGN outburst that has not been observed in low-redshift groups. We assume that the mass of a galaxy group is \( M_{\text{vir}} = 1 \times 10^{13} \, M_\odot \). We set \( \Sigma_{\text{ISM}}(0) = 8 \times 10^{19} \, m_p \) and \( r_{\text{gal}}(0) = 10 \, \text{kpc} \). We fix the rotation and escape velocities of the galaxy at \( v_{\text{rot}} = 220 \, \text{km s}^{-1} \) and \( v_{\text{esc}} = \sqrt{2} v_{\text{rot}} \), respectively. These parameters are those for the Galaxy (e.g. Spitzer [1978]).

Since we do not know much about the sources of the non-gravitational heating in groups and clusters (Section 1), we assume that the IGM has not been non-gravitationally heated at \( t = 0 \) for the sake of simplicity. In other words, the IGM is non-gravitationally heated for the first time by the AGN outburst we consider below. Thus, we assume that the mass fraction of the IGM in the group is the same as the baryon fraction of the Universe and is 0.15. If the IGM has been non-gravitationally heated, the mass fraction and density of the IGM would be lower and the influence of the shock wave on galaxies would be smaller.

First, we assume that the AGN at the group centre ejects an energy of \( E_{\text{AGN}} = 6 \times 10^{61} \, \text{erg} \), which is the one estimated for the cluster MS 0735.6-7421 ([McNamara et al. 2004]). The energy is kinematically given to the IGM for \( R = 10-20 \, \text{kpc} \) at \( t = 0 \); the details of the energy input do not affect the results. We use 1000 unequally spaced meshes in the radial coordinate to cover a region with a radius of 600 kpc. The inner boundary is set at \( R = 1 \, \text{kpc} \).

Fig. 1(a) shows the evolution of the IGM density profile for the group at \( z = 0 \). The parameters of the group are \( R_{\text{vir}} = 560 \, \text{kpc} \) and \( v_{\text{vir}} = 9.9 \). The outburst is strong enough to blow away most of the IGM. The shock reaches the virial radius at \( t \approx 1.6 \times 10^8 \, \text{yr} \). Fig. 1(b) shows the evolution of \( s/s_0 \), where \( s_0 = \Sigma_{\text{ISM}} v_{\text{esc}} \) (see equation 12). Fig. 1(b) indicates that the cold ISM in the galactic disc is stripped for \( R < 220 \, \text{kpc} \) because \( s/s_0 > 1 \) at \( t = \infty \). The profile \( s(t, R) \) does not change after the shock passes the outermost region of the group. We refer to this final profile as \( s(t = \infty, R) \). Of course, the ISM of galaxies with \( v_{\text{rot}} < 220 \, \text{km s}^{-1} \) is more easily stripped for a given \( \Sigma_{\text{ISM}} \).

Fig. 2 shows the evolution of the IGM density profile for the group at \( z = 2 \). The parameters of the group are the same as in Fig. 1(a). The shock reaches the virial radius at \( t \approx 6 \times 10^7 \, \text{yr} \). The profile \( s/t_0 \) in Fig. 2(b) indicates that the ISM in the galactic disc is stripped for \( R < 130 \, \text{kpc} \).

We also considered the case when the energy ejected by the AGN is smaller. Fig. 3 shows the evolutions at \( z = 2 \) when \( E_{\text{AGN}} = 6 \times 10^{60} \, \text{erg} \). The shock reaches the virial radius at \( t \approx 2 \times 10^8 \, \text{yr} \). When \( s/t_0 \leq 1 \) in the entire group, the ISM in the galactic disc is not stripped (Fig. 3(b)).

4 DISCUSSION

We found that in the inner region of a group, the cold ISM in the disc of a galaxy is stripped by the shock wave if \( E_{\text{AGN}} = 6 \times 10^{61} \, \text{erg s}^{-1} \). We compare the effect with that of the usual ram-pressure stripping through the motion of a galaxy in the IGM. The typical velocity of galaxies in a group is

\[ v_{\text{gal}} = \sqrt{G M_{\text{vir}}/R_{\text{vir}}} . \]

For the group with \( M_{\text{vir}} = 10^{13} \, M_\odot \), the velocity is \( v_{\text{gal}} = 280 \, \text{km s}^{-1} \) at \( z = 0 \) and \( v_{\text{gal}} = 440 \, \text{km s}^{-1} \) at \( z = 2 \).

The condition of usual ram-pressure stripping owing to the motion of a galaxy is determined by the long-term (larger than the dynamical time of the galaxy) balance between the ram-pressure from the IGM and the gravity of the galaxy. Thus, the ram-pressure stripping is effective when

\[ \rho_{\text{IGM}} v_{\text{gal}}^2 > \frac{2\pi G \Sigma_{\text{ISM}}}{v_{\text{rot}}^2 r_{\text{gal}}^2} \]

\[ = \frac{2\pi G M_{\text{vir}}}{v_{\text{rot}}^2} \]

\[ \frac{\Sigma_{\text{ISM}}}{r_{\text{gal}}^2} \]
the direction of the height is $< 4 \times 10^{19} \text{ m}_p \text{ cm}^{-2}$. Therefore, we assume that the column density of the halo gas is $\Sigma_{\text{halo}}(0) < 4 \times 10^{19} \text{ m}_p \text{ cm}^{-2}$ and $\Sigma_{\text{halo}}(z) \propto H(z)$ as equation (14). Since $\Sigma_{\text{halo,esc}} < 0.05 \Sigma_{\text{ISM,esc}} = 0.05 \Sigma_0$ for our model galaxy, the halo gas would be stripped even when $s_I/s_0 \sim 0.05$ or smaller.

For $E_{\text{AGN}} = 6 \times 10^{61} \text{ erg}$, Fig. 1b and Fig. 2b show that $s_I/s_0 \gtrsim 0.05$ up to the virial radius of the group ($500 \text{ kpc}$ for $z = 0$ and $230 \text{ kpc}$ for $z = 2$). Thus, most galaxies in the group would be affected by the outburst of the central AGN. Even if $E_{\text{AGN}} = 6 \times 10^{60} \text{ erg}$, the influence of the AGN outburst cannot be ignored for $R < R_{\text{vir}}$ (Fig. 3b).

After the cold ISM (or the halo gas) is stripped by the outburst, the colour of the galaxies would become red due to the lack of star formation. Some of the galaxies would be observed as passive spiral galaxies (e.g. Goto et al. 2003). Some would also fall into the group centre through dynamical friction, and eventually merge with the central galaxy in which the AGN responsible for the outburst resides. Since the fallen galaxies no longer have ISM, they do not supply gas to the supermassive black hole in the AGN. Thus, the outburst would serve as a kind of feedback mechanism for the growth and activity of the black hole.

At low redshift, radio and X-ray observations indicate that the stripping by AGN outbursts may not be common. After the outburst, the X-ray luminosities of the groups we considered reduce to $\sim 0.1\%$ of the initial values and become $\sim 10^{40} \text{ erg s}^{-1}$ for $R < 0.3 R_{\text{vir}}$. Here, we do not integrate the luminosities up to $R_{\text{vir}}$, because it is difficult to detect X-ray in the outermost regions of groups (Mulchaey 2004). The luminosities of the IGM after the outburst are smaller than those of groups from which X-ray emission from the IGM has been detected ($\sim 10^{42} \text{ erg s}^{-1}$; Mulchaey 2004). If the stripping by AGN outbursts were common, the lack of cold ISM in galaxies should be confirmed more in groups lacking for X-ray emission. However, radio (II) and X-ray observations of nearby groups showed the opposite trend (Sengupta, Balasubramanyam, & Dwarkakath 2007; Verdes-Montenegro et al. 2007), although the cause is not known.

On the other hand, we suppose that the stripping by AGN outbursts occurred more often at high redshift (say $z \sim 2$). This is because strong outbursts were more common at that time. For example, radio observations showed that there are a number of AGNs with the jet power of $> 10^{46} \text{ erg s}^{-1}$ at $z \gtrsim 0.5$ (Rawlings & Saunders 1991; Daly 1993). Considering typical duration of an AGN activity ($\sim 10^7 - 10^9$ yr; Rawlings & Saunders 1991), the total energy injected through an activity is $\gtrsim 10^{63} \text{ erg}$. Moreover, it has been indicated that luminous AGNs tend to be found at higher redshifts ($z \sim 2$) in comparison with less luminous AGNs (Ueda et al. 2003; Kaufmann et al. 2007). Furthermore, optical observations often found clustering of red galaxies around radio galaxies at $z \gtrsim 1$ (e.g. Nakata et al. 2001; Kajisawa et al. 2006). The activities of the radio galaxies might have affected the star formation of the surrounding galaxies as we predict. From a theoretical point of view, Fujita (2001) indicated that strong AGN outbursts at $z \sim 1$ blew out the IGM from groups (ancestors of present-day groups or clusters), and they could be responsible for the low metal abundance observed in groups.

![Figure 3](image)

Figure 3. Same as Fig. 1 but for $z = 2$ and $E_{\text{AGN}} = 6 \times 10^{60} \text{ erg}$.
\[ \sim 10^{14} \, M_\odot \] at \( z \sim 0 \) \cite{Renzini1997}. Although these studies do not directly prove the stripping by AGN outbursts, they are at least consistent with our model. In the future, galaxies lack of cold gas would be observed inside the cocoon or the shock produced by an outburst.

5 CONCLUSIONS

We have investigated the influence of an AGN outburst at the centre of a galaxy group on the galaxies surrounding the AGN. If the energy of the AGN is extremely large (\( E_{\text{AGN}} \sim 6 \times 10^{61} \, \text{erg} \)) as the one recently observed in clusters, the shock wave excited by the outburst strips the cold ISM in the disc of the surrounding galaxies located at \( R \sim 100-200 \) kpc from the AGN. The effect of the stripping can be much stronger than that of usual ram-pressure stripping owing to the motion of the galaxies in a group. However, the stripping of the cold ISM in the disc is not effective if \( E_{\text{AGN}} \sim 6 \times 10^{60} \, \text{erg} \).

We also showed that even if the cold ISM in the disc of the galaxies is not stripped, the warm gas in the halo would be stripped by the shock wave. This could be effective for the whole galaxies in the group up to the virial radius even when \( E_{\text{AGN}} \sim 6 \times 10^{60} \, \text{erg} \). The star formation activities of those galaxies would decrease gradually because the ISM consumed by the star formation is not compensated from the gas in the halo (strangulation). Our results indicate that even one strong AGN outburst significantly affects the evolution of galaxies in groups. After the stripping, the galaxies should become red because of the decrease of the star formation rate.

The success of this model depends on the assumption of an extremely strong outburst. Since such outbursts have not been observed in galaxy groups at low-redshift, the stripping by them would not have strong influence on the evolution of galaxies at low-redshift. However, we suppose that it would be at high redshift where extremely strong AGN activities have often been observed.

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