Is Galactic Star Formation Activity Increased During Cluster Mergers?

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Abstract

We have investigated the effect of pressure from intracluster medium (ICM) on disk galaxies in merging clusters. The ram-pressure on the galaxies rapidly increases when two clusters collide. This leads to stripping of the interstellar medium (ISM) and decrease of star formation rate (SFR) of the galaxies. On the other hand, the increase of SFR caused by compression of ISM is less significant. Thus, cluster merger does not trigger, but weakens star formation activity of the galaxies. In the central region of the colliding clusters, blue galaxies with high velocity should exist, although most of galaxies become red. Following the decrease of blue galaxy fraction in the clusters, the fraction of post-starburst galaxies increases. After merger, many galaxies in the cluster restart star formation activity and the segregation of blue and red galaxies becomes prominent.

Key words: galaxies: clusters of — galaxies: evolution — galaxies: intergalactic medium (OU-TAP 98)

1. Introduction

According to the hierarchical clustering scenario, clusters of galaxies are formed through subcluster mergers. The influence of cluster merger on the intracluster medium (ICM) has been investigated in detail through the comparison between hydrodynamic/N-body simulations and X-ray observations. The simulations predict that the collision of large clusters gives rise to distorted X-ray contours and high temperature gas (e.g. Schindler, M"uller 1993; Burns et al. 1994; Ishizaka, Mineshige 1996; Roettiger et al. 1997; Ricker 1998; Takizawa 1999). Recent X-ray observations have confirmed that many clusters have the complex structure predicted by the simulations (e.g. Fujita et al. 1996; Honda et al. 1996; Knopp et al. 1996; Donnelly et al. 1998; Markevitch et al. 1999). On the other hand, the influence of merger on the galaxies in the clusters is not understood. Since cluster merger drastically changes the environment of the galaxies, especially static and ram-pressure on the galaxies, in a short time (\(\lesssim 10^9\) yr), we can expect that it causes observable change in star formation rate (SFR) of the galaxies. However, it is not obvious whether cluster merger increases or decreases SFR of the galaxies as follows. Cluster merger rapidly raises the static and ram-pressure from ICM. As a result, interstellar medium (ISM) of the galaxies is expected to be compressed and star formation activity may be triggered (e.g. Evrard. 1991; Wang et al. 1997). In fact, in several merging clusters, there are galaxies having the abnormal spectrum which reflects recent star formation (e.g. Caldwell et al. 1993; Wang et al. 1997), although Tomita et al. (1996) find that this is not the case for a merging cluster A168. On the contrary, cluster merger may reduce SFR of the galaxies because ram-pressure strips their ISM away. Thus, in order to investigate the effect of pressure on galaxies, SFR of galaxies must be quantitatively estimated. Using the simple model of molecular cloud evolution, Fujita, Nagashima (1999) have quantitatively estimated the SFR of a disk galaxy under the pressure from ICM. However they consider only a radially infalling galaxy; they do not predict the evolutions of all galaxies in the cluster.

In this letter, we investigate the evolution of SFR of disk galaxies when two clusters collide and merge. Moreover, we calculate the color distribution of the galaxies in the clusters. We only consider the effect of pressure from ICM; we do not consider the effect of tidal force from cluster potential and other galaxies for simplicity, although it may cause starburst (Bekki 1999). This is because it is difficult to calculate the intermittent influ-
ence of tidal force on the internal structures of hundreds of galaxies.

2. Models

We consider the merger of two typical clusters. In order to calculate the evolution of ICM, we use the smoothed-particle hydrodynamics (SPH) method (Monaghan 1992). We treat ions and electrons separately based on the model of Takizawa (1999), although the two-temperature nature does not affect the SFR of galaxies significantly. Collisionless particles corresponding to dark matter and galaxies are also considered. The initial conditions for ICM and collisionless particles are the same as those of Run B in Takizawa (1999) except for the radii of the two clusters, \( r_{\text{out}} \). Since we assume that \( r_{\text{out}} \) is ten times the core radius, which is two times larger than that in Takizawa (1999), the total masses of the two clusters are also larger. Their masses are \( 8 \times 10^{14} \) and \( 2 \times 10^{14} \) \( M_\odot \). The gas fraction of the clusters is 0.1, which is supported by recent observations if \( H_0 \sim 75 \) km s\(^{-1}\)Mpc\(^{-1}\) (e.g. Ettori, Fabian 1999). The results in the next section are not sensitive to the fraction within the range of recent observational results. At \( t = 0 \), the separation of the two clusters is 3.3 Mpc. We randomly pick out 125 particles from the collisionless particles (100 for the larger cluster and 25 for the smaller cluster) as disk galaxies. We calculate the orbits of these ‘galaxies’ and the pressure from the surrounding ICM.

The effects of static and ram-pressure on the SFR of disk galaxies are estimated by the model of Fujita (1998) and Fujita, Nagashima (1999). In this model, the SFR is derived by calculating the evolution of each molecular cloud using the relations for a vialized cloud. We think that the model is superior to the approach based on the Schmidt law (Schmidt 1959), which has dominated in this field. This is because while the latter gives the same SFR regardless of the pressure of ISM for a fixed density, the former does not. Moreover the latter does not discriminate between HI gas and molecular clouds. The model adopted here treats them separately, although we sometimes call them together interstellar medium (ISM). Note that the SFR derived through the model adopted here is less sensitive to pressure variation compared to that through the model based on Schmidt law in which the density of ISM is assumed to be proportional to the pressure.

The condition of ram-pressure stripping is

\[
\rho_{\text{ICM}} v_{\text{rel}}^2 > 2\pi G \Sigma_* \Sigma_{\text{HI}}
\]

\[
= v_{\text{rot}}^2 R^{-1} \Sigma_{\text{HI}}
\]

\[
= 2.1 \times 10^{-11} \text{dyn cm}^{-2} \left( \frac{\nu_{\text{rot}}}{220 \text{ km s}^{-1}} \right)^2
\]

where \( \rho_{\text{ICM}} \) is the density of ICM, \( v_{\text{rel}} \) is the velocity of a galaxy relative to the surrounding ICM, \( G \) is the gravitational constant, \( \Sigma_* \) is the gravitational surface mass density, \( \Sigma_{\text{HI}} \) is the surface density of the HI gas, \( v_{\text{rot}} \) is the rotation velocity, and \( R \) is the characteristic radius of the galaxy (Gunn, Gott 1972; Fujita, Nagashima 1999). Abadi et al. (1999) numerically confirm that this analytic relation provides a good approximation. After this condition is satisfied, the formation of molecular cloud is assumed to stop; the gas ejected from stars and supplied from destroyed molecular clouds directly flows into ICM. Note that ISM in the central region of a galaxy (\( \lesssim 2 \) kpc) is not stripped because of large gravitational force. However, the mass is generally far smaller than the total mass of ISM (e.g. Struck-Marcell 1991). Thus, we ignore its contribution to the star formation activity of the galaxy.

If a stripped galaxy reaches the outer part of the cluster, the galaxy may recover ISM. Since Fujita, Nagashima (1999) do not take account of recovery of ISM, we adopt the condition of recovery,

\[
< \frac{\rho_{\text{ICM}}}{\rho_{\text{ICM}} v_{\text{rel}}^2} < \frac{10^{-10}}{\Sigma_{\text{HI}} v_{\text{rel}}^2}
\]

\[
= 2.0 \times 10^{-11} \text{dyn cm}^{-2} \left( \frac{\nu_{\text{rot}}}{700 \text{ km s}^{-1}} \right)^{-1}
\]

\[
\times \left( \frac{S}{6 \text{ M}_\odot \text{ yr}^{-1}} \right) \left( \frac{R}{10 \text{ kpc}} \right)^{-2} \left( \frac{\nu_{\text{rot}}}{220 \text{ km s}^{-1}} \right)^2
\]

where \( S \) is the gas supply from stars and destroyed molecular clouds (Takeda et al. 1984). Although this analytic expression assumes spherical symmetry and may not be exact in the case of a disk galaxy, the following results do not significantly alter even if we change the coefficient of the right hand of relation (2) by a factor of five. After the galaxy satisfies this condition, gas ejected from stars is trapped in the potential well of the galaxy, and molecular cloud formation is resumed.

We start to calculate the SFR of the model galaxies at \( t = 1 \) Gyr. The initial mass of molecular gas and HI column density are \( 2.5 \times 10^9 \text{ M}_\odot \) and \( 8 \times 10^{20} \text{ m}_{\text{HI}} \text{ cm}^{-2} \), respectively. Moreover, we take \( S = 6 \text{ M}_\odot \text{ yr}^{-1} \), \( R = 10 \) kpc, and \( \nu_{\text{rot}} = 220 \) km s\(^{-1}\). Although the parameters are the typical ones for our Galaxy (e.g. Binney, Tremaine 1987), the following results do not change significantly even if we take the ones for typical galaxies whose masses are five times smaller. We have confirmed that the evolutions of the SFR and ISM are not sensitive to the initial time of the calculation \( \geq 1 \) Gyr after the calculation starts. Using the obtained SFR and the population synthesis code made by Kodama, Arimoto (1997), we also investigate the evolution of color of galaxies.
3. Results

Figure 1a shows the X-ray contours and positions of galaxies at \( t = 3.6 \) Gyr, where the two clusters have just passed each other. The origin of the figure is the center of gravity of the clusters. We define a ‘post-starburst galaxy’ (PSB) as the galaxy whose SFR reduces to less than 1/3 of that for \( 10^8 \) to \( 10^9 \) yr before the observation time. Figure 1a shows that red \((B-V > 0.7)\) galaxies and PSBs are concentrated in the central region of the cluster. These features are always seen during merger. Although several blue \((B-V < 0.7)\) galaxies are also seen in the central region, they do not gather at a specific position. We present the velocity distributions of blue and red galaxies within 0.5 Mpc from the center of the merged cluster at \( t = 3.6 \) Gyr in figure 2. Since the average velocity of blue galaxies in this region is \( \sim 2500 \) km s\(^{-1}\), they pass each other simultaneously. Note that in figure 2, the average velocity of red galaxies is \( \sim 1800 \) km s\(^{-1}\). This reflects that the blue galaxies at the central region of the cluster are the ones that can reach the cluster center before they become red although their ISM is stripped. In figure 1b, we present the state of the cluster after it is nearly relaxed \((t = 5 \) Gyr\). Segregation of blue and red galaxies is noticeable. This is quantitatively shown in figure 3. The number of blue galaxies in the central region of cluster \((\lesssim 0.7 \) Mpc\) at \( t = 5 \) Gyr is smaller than that at \( t = 3.6 \) Gyr. This is because there are few galaxies rapidly infalling into the center of the merged cluster at \( t = 5 \) Gyr.

To see the evolution of galaxies in detail, we show the fraction of blue galaxies and PSBs in figure 4. The evolution of the latter is calculated only for \( t > 3 \) Gyr to avoid the influence of initial conditions. The median static and ram-pressures on galaxies are shown for comparison. They temporarily increase at \( t \sim 3.6 \) Gyr when two clusters collide. At that time, the HI gas of most galaxies is stripped because of the increase of ram-pressure. After that, new molecular clouds are not produced; the existing ones disappear within \( \sim 10^8 \) yr because of consumption by star formation and destruction by young stars (see Fujita, Nagashima 1999). Since molecular clouds are used to make stars, the SFR of galaxies and fraction of blue galaxy decrease as molecular clouds disappear. Although the static and ram-pressure compress ISM of galaxies and trigger the star formation activity before the stripping occurs, the duration of activity is short \((\lesssim 0.4 \) Gyr\); the activity does not affect the color distribution of galaxies in clusters significantly. Thus, cluster merger does not trigger, but weakens star formation activity of the galaxies. At \( t \sim 4 \) Gyr, the two clusters once come apart. The ICM of the two clusters expands and their relative velocity reduces. Since the average ram-pressure significantly decreases, the ISM of galaxies recovers and star formation restarts. Thus, the fraction of blue galaxies returns to the initial value \((\sim 60\%)\). Note that the fraction of blue galaxies is over 40\% even when clusters are colliding (figure 1). This means that cluster merger does not significantly affect galaxies in the outer region of the clusters.

Figure 4 clearly shows that the fraction of PSBs increases from 30\% to 60\%, immediately following the merger. These PSBs are the galaxies whose SFR decreases because of ram-pressure stripping. In fact, the fraction of PSBs begins to increase after that of blue galaxies decreases. However, it may not be easy to use PSBs as the probe of cluster merger, because they always exist in clusters. This reflects that some of cluster galaxies have radial orbits and fall into the center of the cluster regardless of cluster merger. Thus, in order to know the relation between PSBs and cluster merger observationally, it is required to compare the PSB fractions of merging clusters with those of non-merging clusters statistically.

4. Summary

We have investigated the effect of pressure on the galaxies when two clusters merge. We find that because of ram-pressure stripping, star formation rate of most of galaxy decreases during merger contrary to the speculation of Evrard (1991) and Wang et al. (1997). Some blue galaxies can reach the central region of the merging clusters before they become red because of their high velocities. By observing velocities, these galaxies would be distinguished from the blue galaxies in which star formation is triggered by tidal force from the gravitational field of the cluster because the tidal interaction is effective when a galaxy moves slowly. Following the decrease of blue galaxy fraction of the clusters, the fraction of post-starburst galaxies increases. After the two clusters pass by, star formation restarts in the galaxies because the ram-pressures decrease. When a quasi-equilibrium state is reached, the segregation of blue and red galaxies becomes prominent.

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Fig. 1. (a) The X-ray surface brightness and the positions of galaxies at $t = 3.6$ Gyr. The crosses and filled circles indicate red ($B-V > 0.7$) and blue ($B-V < 0.7$) galaxies, respectively. Open circles indicate post-starburst galaxies.

Fig. 1. (b) Same as in figure 1 but for $t = 5$ Gyr.
Fig. 2. Histogram showing the distribution of velocity relative to the space coordinate at $t = 3.6$ Gyr. The galaxies within 0.5 Mpc from the origin are picked out.

Fig. 3. Histogram showing the distribution of distance from the origin.

Fig. 4. The fraction of blue galaxies $f_b$ and post-starburst galaxies $f_{PSB}$. The median static pressure $\langle P_{\text{stat}} \rangle$ and ram-pressure $\langle P_{\text{ram}} \rangle$ are also presented.