SYNCHRONIZED FORMATION OF STARBURST AND POST-STARBURST GALAXIES IN MERGING CLUSTERS OF GALAXIES

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ABSTRACT

We propose that synchronized triggering of star formation in gas-rich galaxies is possible during major mergers of cluster of galaxies, based on new numerical simulations of the time evolution of the physical properties of the intracluster medium (ICM) during such a merger event. Our numerical simulations show that the external pressure of the ICM, in which cluster member galaxies are embedded, can increase significantly during cluster merging. As such, efficient star formation can be triggered in gas-rich members as a result of the strong compression of their cold gas by the increased pressure. We also suggest that these star-forming galaxies can subsequently be transformed into post-starburst galaxies, with their spatial distribution within the cluster being different than that of the rest of the population. We discuss whether this possible merger-induced enhancement in the number of star-forming and post-star-forming cluster galaxies is consistent with the observed evolution of galaxies in merging clusters.

Key words: galaxies: evolution - galaxies: halos - galaxies: kinematics and dynamics - galaxies: structure

Online-only material: color figures

1. INTRODUCTION

Recent X-ray observations have revealed that some clusters of galaxies have "cold fronts" which may have been formed as a result of them undergoing a major/minor merger (Owers et al. 2009a, 2009b). These observations, as well as those of substructures in clusters (e.g., Forman & Jones 1990; Briel et al. 1991; Escalera et al. 1994), strongly suggest that a significant fraction of clusters might have experienced merger events. There are also observations which suggest that cluster merging affects the global star formation in cluster member galaxies (e.g., Caldwell et al. 1993; Caldwell & Rose 1997; Miller et al. 2003; Ferrari et al. 2005). These observations beg the key question as to how and why some merging clusters show larger fractions of starburst galaxies (SBCs) and post-starburst galaxies (PSBCs) than others (e.g., Caldwell & Rose 1997, Owen et al. 2005).

From a theoretical viewpoint, it is unclear whether and how cluster merging can significantly change the number fractions of SBCs and PSBCs. Bekki (1999) showed that the timedependent tidal fields of merging groups and clusters of galaxies can trigger secondary starbursts in their member galaxies and thus change the number fractions of these galaxies. Fujita et al. (1999) showed that the star formation rates of galaxies during a major cluster merger can decrease because of ram-pressure stripping of the interstellar gas initially within the galaxies. As such, the fractions of blue, actively star-forming galaxies can decrease and then the fractions of PSBCs can increase. Recent numerical simulations have shown that strong ram pressure from the intracluster medium (ICM) can significantly increase the star formation rates in cluster galaxies (Bekki & Couch 2003; Kronberger et al. 2008). Therefore, it is timely to revisit the question as to whether the rapidly evolving state of the ICM within a merging cluster can significantly change the number fractions of SBCs and PSBCs.

The purpose of this Letter is to thus show, for the first time, that cluster merging has the potential to trigger star formation among a significant fraction of the member galaxies

in a simultaneous way: this "synchronized" activity might be an important clue for better understanding and discriminating merger-driven galaxy evolution in cluster galaxy populations. We investigate the orbital evolution of cluster member galaxies and the external pressure of the ICM surrounding the galaxies during the cluster-merging phase, in order to determine how such a dynamical event might influence the star formation histories of cluster populations. Our previous simulations showed that if the pressure of the ICM becomes sufficiently high, it can trigger the collapse of giant molecular clouds (GMCs) and hence bursts of star formation in galaxies (Bekki & Couch 2003; also see Kronberger et al. 2008 for ram-pressure-induced star formation). We thus adopt a model in which the star formation rates of galaxies in merging clusters are significantly increased if the pressure (P) of the ICM surrounding the galaxies exceeds the internal pressure of the GMCs.

2. THE MODEL

In order to simulate the time evolution of dark matter halos and the ICM in merging clusters, we use the latest version of GRavity PipE (GRAPE; GRAPE-7), which is the specialpurpose computer for gravitational dynamics (Sugimoto et al. 1990). We use our original GRAPE–SPH code (Bekki & Chiba 2006; Bekki 2009) which combines the method of smoothed particle hydrodynamics (SPH) with GRAPE for calculations of three-dimensional self-gravitating fluids in astrophysics. Since the models for the structures of dark matter halos and the physical properties of hot gas within the halos are already given in detail by Bekki (2009), we only briefly describe the models here.

The structure of each of the two clusters in a merger is modeled using a Navarro–Frenk–White (NFW) profile predicted by the cold dark matter cosmology (Navarro et al. 1996), and the masses and sizes of the clusters are represented by M_{cl} and R_{cl} , respectively. Henceforth, all masses and lengths are measured in units of M_{cl} and R_{cl} , respectively, unless otherwise specified. Velocity and time are measured in units of V_{cl} = $(GM_{\rm cl}/R_{\rm cl})^{1/2}$ and $t_{\rm cl} = (R_{\rm cl}^3/GM_{\rm cl})^{1/2}$, respectively, where G is the gravitational constant and assumed to be 1.0 in the present study. These $V_{\rm cl}$ and $t_{\rm cl}$ correspond to the circular velocity and dynamical time scale at $R_{\rm d}$, respectively.

The *c* parameter (= r_s/r_{vir} , where r_s and r_{vir} are the scale and virial radii of the NFW profile, respectively) for a cluster with M_{cl} (= M_{dm}) is chosen according to the predicted $c-M_{dm}$ relation in the Λ CDM simulations (e.g., Neto et al. 2007). A reasonable value of *c* is thus 4.7 for $M_{dm} = 10^{14} M_{\odot}$. The larger and smaller clusters in a merger, whose mass ratio is denoted as m_2 (0.1 $\leq m_2 \leq 1$), are referred to as CL1 and CL2, respectively, for convenience. If CL1 has mass M_{cl} and radius R_{cl} , then CL2 has mass $m_2 M_{cl}$ and radius $\sqrt{m_2}R_{cl}$.

The ICM has mass M_g and the same spatial distribution (ρ_g) as the dark matter and is assumed to be initially in hydrostatic equilibrium. The initial gaseous temperature of an ICM 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 (1E-8) in Binney & Tremaine 1987). Therefore, gaseous temperature $T_g(r)$ at radius *r* from the center of a cluster can be described as

$$T_{\rm g}(r) = \frac{m_{\rm p}}{k_{\rm B}} \frac{1}{\rho_{\rm g}} \int_r^\infty \rho_{\rm g}(r) \frac{GM(r)}{r^2} dr, \qquad (1)$$

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 cluster. Radiative cooling is not included in the present study so that the hydrodynamical equilibrium of halo gas can be obtained from isolated cluster models. We can expect that the shocked gaseous regions and pressure in models with radiative cooling have significantly higher gas densities and pressure, and therefore galaxies in the models can be more strongly influenced by cluster merging during their passage of the shocked regions. We adopt a representative value of $M_g = 0.136 M_{cl}$ (e.g., McCarthy et al. 2008).

Galaxies in a cluster are represented by collisionless particles and their spatial distribution follows the NFW profile with c = 3. The canonical Schechter function is adopted for generating a galaxy luminosity/mass function for luminosities ranging from 0.01 L* to 2.5 L* in a cluster. The total mass (thus number) of galaxies in a cluster with M_{cl} is determined by the mass-to-light ratio, that itself is dependent on M_{cl} (Marinoni & Hudson 2002). Therefore, as an example, a cluster with $M_{cl} = 10^{14} M_{\odot}$ has 114 galaxies. Cluster member galaxies in a cluster have an isotropic velocity dispersion just as the dark matter of the cluster does.

Galaxies in the present study have no halo gas that might well shield interstellar medium (ISM) of disk galaxies and thus weaken the possible physical effects of ICM (e.g., triggering star formation) on the ISM. Previous numerical simulations, however, showed that halo gas around disk galaxies can be efficiently stripped by ICM even in isolated clusters (e.g., Bekki 2009): the halo gas would not significantly weaken the effects of ICM on galaxy evolution in merging groups and clusters. The ISM of galaxies is not included in the present models so that the details of star formation caused by cluster merging cannot be properly investigated. The present study thus assumes that if the pressure of the ICM around galaxies can become high enough, then the star formation histories can be significantly changed irrespective of galaxy properties. This assumption would be reasonable, if GMC properties do not depend strongly on galaxy properties.

The relative position and velocity of CL2 with respect to CL1 are described as (X_r, Y_r, Z_r) and (U_r, V_r, W_r) , respectively. For all models described in the present study, $X_r = 2R_{cl}$ (where R_{cl} is the size of CL1), $Z_r = 0$, $U_r = 0$, and $W_r = 0$. Therefore, Y_r is the impact parameter of cluster merging and V_r is the initial relative velocity of merging two clusters. Cluster-merging processes and subsequent ICM evolution depend strongly on the four parameters, M_{cl} , m_2 , Y_r , and V_r . Although we have conducted a large parameter study, we only show the results of the models with $M_{cl} = 10^{14} M_{\odot}$, $0.1 \le m_2 \le 1$, $Y_r = 0.5R_{cl}$, and $V_r = -V_{cl}$. Parameter dependencies of the results will be described in detail in our forthcoming papers (K. Bekki et al. 2010, in preparation).

Here, we focus in particular on the "standard model" with $M_{cl} = 10^{14} M_{\odot}$, $m_2 = 0.25$, $R_{cl} = 2.0 \text{ Mpc}$, $V_{cl} = 595 \text{ km s}^{-1}$, $t_{cl} = 2.0 \text{ Gyr}$, $Y_r = 1.0 \text{ Mpc}$, and $V_r = -595 \text{ km s}^{-1}$, because it shows one of the typical behaviors of the time evolution of the external gas pressure around galaxies in merging clusters. The total particle number of dark matter and gas particles used in a cluster merger depends on m_2 : it is 264,000 for $m_2 = 0.25$ and 440,000 for $m_2 = 1$. We also run an "isolated model" in which a cluster evolves without merging with any other clusters. Throughout this Letter, the time *T* represents the elapsed time since the start of the simulation.

We mainly investigate the time evolution of the external pressure (P) of the ICM surrounding galaxies, as first done by Evrard (1991). We investigate P (static pressure) at each time step for each galaxy during $4t_{cl}$ evolution of cluster merging and thereby estimate the maximum value (P_{max}) for each galaxy and the time (t_{max}) when $P = P_{max}$. We then check whether P_{max} is larger than the threshold pressure (P_{thres}) required to induce the global collapse of GMCs to form massive star clusters (e.g., Elmegreen & Efremov 1997). We set P_{max} to be $2 \times 10^5 k_{\rm B}$ where $k_{\rm B}$ is Boltzmann's constant (e.g., Bekki et al. 2002).

3. RESULT

Figure 1 shows how the distributions of galaxies for the larger (CL1) and smaller clusters (CL2) can change during cluster merging with $m_2 = 0.25$. During the strong hydrodynamical interaction between the ICM of the merging clusters ($T \approx 3$ Gyr), some fraction of the galaxies, in particular, those within CL2, pass through the high-density, high-pressure region where the two gas spheres collide. The CL2 group persists as a coherent substructure in the spatial distribution of galaxies during the final dynamical relaxation phase of cluster merging ($T \approx 5$ Gyr). The galaxies from CL1 and CL2 are finally well mixed and show no clear differences in their spatial distributions with respect to the center of the newly formed cluster (T = 7 Gyr).

Figure 2 compares the time evolution of *P* (pressure of ICM surrounding galaxies) in the standard merger model with that in the isolated model for the same selected galaxy. Figure 2 clearly shows that *P* dramatically increases owing to the passage of the galaxy through the high-pressure shocked region of the merging cluster when the clusters collide ($T \approx 3$ Gyr). *P* does not change much at all in the isolated model. The simulated *P* exceeds the threshold pressure P_{th} (= $2.0 \times 10^5 k_{\text{B}}$) for the collapse of GMCs, so that efficient star formation within GMCs is highly likely. This clearly demonstrates that cluster merging can strongly influence the star formation activity within their member galaxies.

Figure 3 shows that the distribution of t_{max} for CL2 has a peak around $T \approx 3$ Gyr, whereas CL1 has a peak at $T \approx 4$ Gyr.



Figure 1. Time evolution of the spatial distributions of the ICM (smaller cyan dots), the galaxies in CL1 (bigger red dots), and the galaxies in CL2 (bigger blue dots), projected onto the x-y (upper four panels) and x-z planes (lower four panels), for the standard model. *T* shown in the upper left corner of each panel represents the time that has elapsed since the start of the simulations. (A color version of this figure is available in the online journal.)

For CL2, the number fraction of galaxies with t_{max} (F_{max}) for $T \approx 3$ Gyr can be as high as 0.4, which implies that a significant fraction of galaxies in CL2 can experience strong pressure by the surrounding ICM *simultaneously* when two clusters collide. Figure 3 also shows that P_{max} for most of galaxies with $t_{max} \approx 3$ Gyr can be higher than P_{thres} : some of them also show P_{max} larger than $10^6 k_{\rm B}$. These results suggest that a significant fraction of galaxies in merging clusters can be simultaneously influenced by the dramatically increased external pressure of ICM.



Figure 2. Time evolution of P for a selected galaxy particle for the isolated model (blue) and the standard merger model (red).

(A color version of this figure is available in the online journal.)



Figure 3. Upper panel shows the distribution of galaxies in CL1 (red) and CL2 (blue) on the log $P_{\text{max}}-t_{\text{max}}$ plane (upper) for the standard model. The lower panel shows the t_{max} distribution for CL1 (red), CL2 (blue), and all galaxies in CL1 and CL2 (green) expressed in terms of the number fraction (F_{gal}) of galaxies at each t_{max} bin. The presence of galaxies showing large $P_{\text{max}} (>10^6 k_{\text{B}} \text{ K cm}^{-3})$ at $t_{\text{max}} < 1$ Gyr is due largely to the fact that they can pass through the very inner region of the cluster (at their early orbital evolution phases) where the static pressure is rather high.

(A color version of this figure is available in the online journal.)

4. DISCUSSION AND CONCLUSIONS

4.1. Possible Distributions of SBCs and PSBCs

In order to discuss possible distributions of SBCs and PSBCs at T in each simulation, we assume that galaxy particles with $P_{\text{max}} \ge P_{\text{thres}}$ that have $T - t_{\text{max}} \le 0.1$ Gyr and 0.1 Gyr $\le T - t_{\text{max}} \le 1$ Gyr are labeled as SBCs and PSBCs, respectively. Given that previous numerical simulations confirmed the formation of "E+A" galaxies ("E+A"s) from SBCs



Figure 4. Spatial distributions of PSBCs (bigger green dots) and non-PSBCs (smaller red dots) projected onto the x-y plane at T = 4 Gyr (~1 Gyr after the two cluster violently collide) for the standard model.

(A color version of this figure is available in the online journal.)

less than 1 Gyr after strongly secondary starbursts (e.g., Bekki et al. 2005), the above criterion can be reasonable.

Figure 4 shows that the distribution of PSBCs at T = 4 Gyr appears to have a weakly elongated structure (or substructure) in the direction of X = -1 Mpc and Y = -0.5 kpc. This reflects the fact that CL2 has not been yet completely dynamically relaxed and some PSBCs are still within CL2. The number fraction of PSBCs (f_{PSBC}) becomes large (~ 0.22) at T = 4 Gyr, mainly because a large fraction of galaxies pass through the high-pressure region of the merging cluster around T = 3 Gyr. The main reason for the apparent lack of PSBCs in the core of CL1 (i.e., $|X| \le 0.2$ Mpc and $|Y| \le 0.2$ Mpc) is that galaxies experienced strong external pressure from the ICM there, some 0.9–1.0 Gyr ago (i.e., at T = 3.0–3.1 Gyr). The distribution of PSBCs changes significantly as the merging clusters dynamically relax.

The fraction of galaxies that experience high external pressure with $P_{\text{max}} \ge P_{\text{thres}}$ depends on m_2 , such that it is likely to be higher in models with larger m_2 : it is 0.29 for $m_2 = 0.1$ and 0.74 for $m_2 = 1.0$. The fraction of galaxies that experience very high external pressure with $P_{\text{max}} \ge 5P_{\text{thres}}$ depends strongly on m_2 : it is only 0.008 for $m_2 = 0.1$ and 0.51 for $m_2 = 1.0$. The main reason for these dependencies is that major merging can form more strongly shocked gaseous regions over a larger volume of the merging clusters, so that a larger number of their member galaxies pass through the shocked regions during the merger.

Just after cluster merging, the PSBCs appear to be distributed in a ring-like structure, particularly in the case of the major merger models with $m_2 = 1$. This is due to the strong central concentration of SBCs in the merger remnants: all galaxies in the core are identified as SBCs, which is just due to the model assumption: galaxies are always identified as SBCs irrespective of gas content (i.e., whether they are gas-poor PSBCs) whenever they are in the core region where the external pressure is high enough to trigger starbursts. Thus, it is not appropriate to use the results of this Letter to discuss the observational results of M. S. Owers et al. (2010, in preparation), which show an intriguing distribution of PSBCs in clusters that have undergone a recent major merger.

4.2. Larger Fractions of SBCs in Merging Clusters?

We have shown that cluster merging can dramatically increase the pressure of the ICM surrounding the cluster member galaxies, to the extent that a significant fraction of the galaxies can be simultaneously affected. Previous numerical simulations have shown that GMCs in gas-rich galaxies that are exposed to this increased pressure of the ICM are strongly compressed, thereby triggering efficient star formation within them in their high-density regions (Bekki & Couch 2003). We therefore suggest that (1) cluster merging can trigger starbursts in gas-rich galaxies embedded within those regions of the ICM that have undergone this dramatical increase in pressure, and (2) these starbursts can occur simultaneously for a significant fraction of the galaxies within the merging clusters.

It should be stressed, however, that ram-pressure stripping can become much more effective during cluster merging so that cold H I gas within disk galaxies and their halos—which can fuel star formation—can be efficiently stripped (Fujita et al. 1999; Bekki 2009). This ram-pressure stripping of H I gas would cause severe truncation of star formation after the GMCs are converted into new stars during cluster merging. This process would lead naturally to the formation of PSBCs (also known as "E+A" galaxies). Therefore, cluster merging can provide a possible explanation for the observed larger fraction of E+A galaxies in some clusters with substructures (e.g., Caldwell & Rose 1997).

Whether major starbursts are triggered in disk galaxies as a result of the strong external pressure exerted by the ICM during cluster merging strongly depends on the gas mass fractions (f_g) within their disks. It is well known that higher redshift clusters of galaxies have a larger fraction of blue galaxies than their lower redshift counterparts (e.g., Butcher & Oemler 1978). This likely means that there is a larger fraction of gas-rich galaxies in higher redshift clusters, although only future H I observations can directly verify this. The present result thus implies that synchronized formation of SBCs is more likely to occur in higher redshift merging clusters of galaxies.

Galaxies located in the core regions of clusters can experience strong ram-pressure stripping of their ISM by the ICM, to the extent that they lose most of their ISM gas (i.e., $f_g \sim 0$). They are therefore unlikely to experience starbursts during cluster merging, because they are already gas-poor prior to cluster merging. Thus, the present study is likely to overestimate the fractions of SBCs to some extent. We need to properly model the variation in f_g in galaxies of different Hubble type, and how that translates into a varying f_g with radius from the cluster center, in order to predict much more precisely the possible fractions of SBCs and PSBCs in merging clusters in our future studies.

It should also be noted that it is not only the external pressure of the ICM in clusters that can trigger starbursts in gas-rich galaxies (e.g., Kronberger et al. 2008), but also the time-dependent cluster tidal fields (Bekki 1999). It therefore appears inevitable that merging clusters are likely to have a larger fraction of SBCs than non-merging clusters. It would be difficult, however, for observational studies to determine whether tidal effects or increased external ICM pressure is the main driver for such an increased starburst fraction. Since the time-varying tidal fields in merging clusters can also transform *stellar* disks (Bekki 1999), whereas the external pressure of the

ICM is unlikely to do so, the morphological properties of each individual SBC will provide important clues as to which of the above two effects are responsible for their origin.

Recent and ongoing photometric and spectroscopic observations of galaxy properties in a large sample of clusters with and without cold fronts will soon reveal the number fractions of SBCs and PSBCs and their spatial distributions and kinematics in these possibly merging and non-merging clusters (e.g., Hwang & Lee 2009; Ma et al. 2010; M. S. Owers et al. 2010, in preparation). These statistical studies will enable us to compare the simulated kinematics (e.g., line-of-sight velocity distributions) of SBCs with those observed, thereby allowing more robust conclusions to be drawn as to whether the star formation histories of cluster member galaxies are dramatically changed by cluster merging. The observed peculiar spatial distributions (e.g., ring-like structures) of PSBCs in clusters with substructures (e.g., the Coma cluster; Poggianti et al. 1999) will place strong constraints on the mass ratios and radial velocities of merging clusters.

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