GROUP-CLUSTER MERGING AND THE FORMATION OF STARBURST GALAXIES

KENJI BEKKI
Astronomical Institute, Tohoku University, Sendai, 980-8578, Japan
email address: bekkii@astroa.astr.tohoku.ac.jp

ABSTRACT

A significant fraction of clusters of galaxies are observed to have substructure, which implies that merging between clusters and subclusters is a rather common physical process of cluster formation. It still remains unclear how cluster merging affects the evolution of cluster member galaxies. We report the results of numerical simulations, which show the dynamical evolution of a gas-rich late-type spiral in a merger between a small group of galaxies and a cluster. The simulations demonstrate that time-dependent tidal gravitational field of the merging excites non-axisymmetric structure of the galaxy, subsequently drives efficient transfer of gas to the central region, and finally triggers a secondary starburst. This result provides not only a new mechanism of starbursts but also a close physical relationship between the emergence of starburst galaxies and the formation of substructure in clusters. We accordingly interpret post-starburst galaxies located near substructure of the Coma cluster as one observational example indicating the global tidal effects of group-cluster merging. Our numerical results furthermore suggest a causal link between the observed excess of blue galaxies in distant clusters and cluster virialization process through hierarchical merging of subclusters.

Subject headings: galaxies: clusters, – galaxies: starburst – galaxies: evolution – galaxies: formation – galaxies interaction – galaxies: structure

1. INTRODUCTION

Recent observational studies on morphology, structure, and kinematics of nearby and distant clusters of galaxies have revealed that a significant fraction of clusters have substructures (e.g., Forman & Jones 1990; Briel et al. 1991; White, Briel, & Henry 1993; Escalera et al. 1994; Slezak, Durret, & Gerbal 1994; Colless & Dunn 1996; Léméonon et al. 1997). Theoretical studies based largely on numerical simulations suggest that these substructures in clusters result from cluster formation process through merging of other smaller subclusters and groups of galaxies (Evraird 1990; Burns et al. 1994; Roettiger, Stone, & Mushotzky 1998). This cluster merging process has been found to affect greatly star formation histories of cluster member galaxies (e.g., Caldwell et al. 1993; Caldwell & Rose 1997). Caldwell et al. (1993) and Caldwell & Rose (1997) found that post-starburst galaxies are located preferentially near a secondary peak in the x-ray emission of the Coma cluster, and accordingly suggested that merging between the main Coma and a group of galaxies (including NGC 4839) plays a vital role in triggering secondary starbursts in galaxies. Caldwell & Rose (1997) furthermore revealed that about 15 % of early-type galaxies in nearby five rich clusters with substructures have clear signs of ongoing or recent starbursts, and speculated a causal relation between the formation of starburst galaxies and cluster merging process.

Although merging between clusters and subclusters (or groups) is observationally suggested to affect greatly star formation histories of cluster member galaxies, there have been no extensive theoretical studies investigating how cluster merging determines or changes the star formation histories in the course of cluster formation. In this Letter, we numerically investigate stellar and gas dynamics of a bulgeless late-type spiral in a merger between two clusters of galaxies. In particular, we describe how the time-dependent tidal gravitational field of the merging determines the star formation history of the gas-rich spiral and thereby illustrate a new mechanism for triggering starbursts in cluster environments. We here emphasize that not the simple mean tidal gravitational field of a cluster but the rapidly changing tidal gravitational field of group-cluster merging is a necessary ingredient for triggering a starburst in group-cluster merging. Accordingly, the present mechanism of starburst galaxy formation is different from the previously proposed models which resort to the simple tidal gravitational field of clusters (e.g., Byrd & Valtonen 1990; Byrd & Henriksen 1996; Moore et al. 1996; Moore, Lake, & Katz 1998). Cluster merging can play decisive roles in various aspects of cluster galaxy evolution, such as morphological transformation, dynamical heating, tidal truncation of gas replenishment, and excitation of nuclear activities in galaxies. We however focus mainly on star formation histories of cluster member galaxies in this Letter.

2. MODEL

The structure of two clusters in a merger is modeled by using the universal density profile predicted by the standard cold dark matter cosmogony (Navarro, Frenk, & White 1996). For convenience, we refer to the smaller (larger) cluster as a group (cluster). Total mass of a cluster (group) represented by $M_{cl}$ ($M_{gr}$) is set to be $2.0 \times 10^{14} M_{\odot}$ ($5.0 \times 10^{13} M_{\odot}$). The scale radius and virial one are 127 kpc (80.1 kpc) and 1.16 Mpc (728 kpc), respectively, for the cluster (group). The group merges with the cluster with the impact parameter of 254 kpc, the initial relative velocity of $V_{rel}$, and the initial separation of 1.73 Mpc. We present the results of two models with $V_{rel} = 430$ km/s and 602 km/s (corresponding to...
0.5 and 0.7 times the circular velocity at the virial radius of the cluster, respectively). Although the strength of the induced starburst depends on $M_{\text{c1}}$ and $M_{\text{gr}}/M_{\text{c1}}$ in such a way that starbursts are more likely to be stronger for the model with larger $M_{\text{c1}}$ and $M_{\text{gr}}/M_{\text{c1}} \sim 1.0$ (for $10^{13}M_\odot \leq M_{\text{gr}}, M_{\text{c1}} \leq 5.0 \times 10^{12}M_\odot$), we here present only the results of the models with $M_{\text{c1}} = 2.0 \times 10^{12}M_\odot$ and $M_{\text{gr}}/M_{\text{c1}} = 0.25$. More details on $M_{\text{c1}}, M_{\text{gr}},$ and $V_{\text{rel}}$ dependences are given in Bekki (1998).

We construct the model of a bulgeless gas-rich disk by using the Fall-Efstathiou model (Fall & Efstathiou 1980). Initial mass-ratio of dark matter halo to disk stars to disk gas is 20:4:1 for the disk. The disk mass and size are $6.0 \times 10^{10} M_\odot$ and 17.5 kpc, respectively. The exponential disk scale length and the maximum rotational velocity for the disk is 3.5 kpc and 220 km/s, respectively. In addition to the rotational velocity made by the gravitational field of the disk, the initial radial and azimuthal velocity dispersion are given to disk components according to the epicyclic theory with Toomre’s stability parameter $Q$ (Binney & Tremaine 1987) equal to 1.5. Collisional and dissipative nature of gas is represented by discrete gas clouds rather than by a continuum of gas governed by an equation of state. This scheme we adopt is called as ‘Sticky particle method’ (Schwarz 1981). In this scheme, gas clouds collide with each other inelastically, reduce their relative velocity, and lose their kinetic energy dissipatively. The size and the mass for each gas cloud are set to be $1.3 \times 10^6$ pc and $1.2 \times 10^5 M_\odot$, respectively. The radial and tangential restitution coefficient for cloud-cloud collisions are set to be 1.0 and 0.0, respectively. Star formation in gas clouds is modeled by using the Schmidt law (Schmidt 1959) with Kennicutt (1989) of $0.22 M_\odot/pc^3$. The coefficient of the Schmidt law is chosen such that the mean star formation rate for the first 1 Gyr evolution of an isolated disk is $\sim 1 M_\odot/yr$. The disk orbits the center of the group and the initial distance between the mass center of the group and the disk is 80.1 kpc. The dependence of star formation history of a disk galaxy on the initial distance is described in detail by Bekki (1998).

In order to elucidate more clearly the importance of time-dependent tidal gravitational effects of group-cluster merging in star formation histories of galaxies, we assume firstly that only the group has a disk galaxy, and secondly that neither the group nor the cluster have hot intracluster medium. Accordingly a group-cluster merger is composed of a galaxy, background dark matter of a group, and that of a cluster. This assumption means that we here neglect completely tidal effects of galaxy interaction and merging (Barnes & Hernquist 1992; Moore et al. 1996), ram-pressure stripping (Farouki & Shapiro 1980), and hydrodynamical interaction between galaxies and intracluster medium (Evrard 1991), and thereby extract only the essential ingredient of the tidal effects of group-cluster merging. It should be emphasized here that the present study does not consider physical mechanisms of starbursts other than group-cluster merging to be less important: The relative importance of each of possibly promising mechanisms for triggering starbursts in clusters should be clarified by future more realistic theoretical studies. Thus, although the present numerical study is rather idealized and less realistic in some points, it can clearly demonstrate that the tidal gravitational effects of group-cluster merging drives secondary starbursts of galaxies.

The total particle number is 20000 for background dark matter of a cluster, 10000 for that of a group, 10000 for dark matter halo of a disk, 10000 for stellar components of the disk, and 10000 for gaseous ones of the disk, in a group-cluster merging. The softening length is 32.2 kpc for the gravitational interaction between the dark matter components of the cluster and those of the group (corresponding to the mean particle separation at the half mass radius of the cluster), 0.81 kpc for that between disk stars, gas, and dark matter halo surrounding the disk (the mean particle separation at the half mass radius of the disk), and 16.5 kpc for that between dark halo components of the cluster and the group and disk components (the mean value of the above two softening lengths). We use these three different gravitational softening lengths in order to investigate how the global tidal field of group-cluster merging affects the local dynamical evolution of the disk in an admittedly self-consistent manner. All the simulations have been carried out on the GRAPE board (Sugimoto et al. 1990).

3. Result

Figure 1 describes the typical behavior of the formation of a starburst galaxy in group-cluster merging. After the group passes through the cluster for the first time, it suffers from tidal distension and gradually loses its central concentration (the time $T = 3.4$ Gyr). Then, the group becomes widely dispersed owing to strong global tidal effects of the cluster whereas the cluster does not change so drastically its initial mass distribution ($T = 4.5, 7.9$). Finally, the merger becomes dynamically relaxed to form a new and more massive cluster. Substructure of the merger can be clearly seen between $T = 3.4$ and $T = 7.9$. These formation processes of substructure in a cluster merger are consistent reasonably well with those of previous studies (Burns et al. 1994; Roettiger et al. 1998).

Time-dependent tidal gravitational field of the merger gives strong non-axisymmetric perturbation to a disk galaxy in the group and subsequently induces a central stellar bar and outer asymmetric gaseous spiral arms in the galaxy ($T = 3.4$). These non-axisymmetric structures enhance cloud-cloud collisions and gaseous dissipation, drive the efficient transfer of gas to the central region of the galaxy, and consequently induce a secondary starburst ($T = 4.0$ in Fig.1 and Fig.2). As is shown in Figure 2, the strength of the starburst in the present group-cluster merger model is rather moderate compared with that triggered by major galaxy merging (Milos & Hernquist 1996). The secondary starburst populations form a central small flat bulge-like component and consequently increase the degree of central mass concentration in the disk ($T = 7.9$). In total, about 72% of initial gas is consumed by star formation. These results clearly demonstrate a physical connection between the emergence of starburst (or post-starburst) disk galaxies and cluster merging process.

As the galaxy sinks toward the center of the cluster owing to dynamical friction in the late phase of the merging, the stellar disk suffers from strong dynamical heating resulting from tidal gravitational field of the cluster core. Consequently, the disk is dynamically thickened and the spiral structure becomes rather inconspicuous. Furthermore, about 45% of dark halo components of the disk
are tidally stripped during the merging. Galactic haloes are generally considered to be gas reservoirs indispensable for supplying fresh gas and maintaining star formation activity in disks (Larson, Tinsley, & Caldwell 1980). Tidal removal of halo components accordingly could drive the truncation of gas infall and replenishment and consequently curtail the future star formation of disk galaxies in group-cluster mergers. These results imply that global gravitational effects of cluster mergers can not only drive morphological transformation of late-type disks but also control star formation histories of those galaxies.

Thus, the present numerical results imply that group-cluster merging can transform actively star-forming gas-rich late-type disks into gas-poor early-type ones with considerably inactive star formation, principally because global tidal gravitational field of the merging can greatly affect both galactic star formation histories and morphology. These accordingly suggest that as a cluster undergoes hierarchical merging of small groups and subsequently becomes more dynamically relaxed and more massive, the fraction of late-type spirals in the cluster becomes progressively smaller: Group-cluster merging provides a causal relation between rapid morphological transformation of late-type spirals and cluster growth process through merging of subclusters. Recent observational studies (Edge & Stewart 1991; Smail et al. 1997) have found a marginal evidence that there is an anticorrelation between the inferred total mass of a cluster and the fraction of spirals within the cluster.

4. DISCUSSION AND CONCLUSION

Remarkable features of the present group-cluster merger model of starburst galaxies are the following two. Firstly, the model demonstrates a physical connection between the presence of starburst (or post-starburst) galaxies in clusters and the existence of substructure in those clusters. In particular, in the merger with $V_{rel} = 602$ km/s, the starburst (or post-starburst) galaxy remains well outside the cluster and located near the developed substructure for a few Gyr (See Figure 3). This result strongly suggests that the origin of widespread post-starburst galaxies located near substructure of the Coma cluster (Caldwell et al. 1993) is due principally to tidal gravitational effects of a group-cluster merger with rather large relative velocity. The origin of the observed larger fraction of post-starburst galaxies in nearby clusters with obvious double structure (Caldwell & Rose 1997) can be also explained by the tidal effects of cluster mergers.

Secondly, galaxies with starbursts (or post-starbursts) neither have conspicuous tidal tails nor are severely distorted in the present model. This provides an important implication on the origin of the Butcher-Oemler effect (Butcher & Oemler 1978), which means that higher redshift clusters of galaxies have a larger fraction of blue galaxies than lower redshift counterparts. Recent morphological studies by the Hubble Space Telescope and ground-based telescopes (Couch et al. 1994; Lavery & Henry 1994; Couch et al. 1998) have revealed that about the half of distant blue galaxies appear to be interacting or merging, which strengthens the importance of galaxy interaction and merging in the star formation histories of disk galaxies. However, the remaining half of the galaxies, though discernibly distorted and having asymmetric feature, neither have remarkable tidal tails nor are severely disturbed (Couch et al. 1998). The starbursts triggered by group-cluster merging can give a natural explanation for these distant blue galaxies. We here stress that not all of distant blue galaxies are observationally revealed to experience the past starbursts (Abraham et al. 1996; Barger et al. 1996): Infall of field galaxies with active star formation can equally explain the origin of blue galaxies with largely unperturbed morphology in distant clusters.

We conclude that time-dependent tidal gravitational field of group-cluster merging, the importance of which has been completely neglected in previous studies, induces secondary starbursts. Galaxy interaction and merging (e.g., Barnes & Hernquist 1992), galaxy harassment (Moore et al. 1996), and environmental effects of clusters (Farouki & Shapiro 1980; Byrd & Valtonen 1990; Evrard 1991) are all suggested to play decisive roles in the formation of starburst galaxies. Then, which physical process dominates the formation of starburst galaxies in cluster environments? The present study predicts that only one time group-cluster merging can trigger starbursts in a significant fraction of group member galaxies nearly simultaneously, principally because the tidal effect of the merging is global and thus can induce the formation of non-axisymmetric structure in the galaxies. Accordingly, one of observational tests to assess the relative importance of group-cluster merging is to investigate whether or not starburst galaxies are developed nearly simultaneously in an ongoing cluster merger.

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Fig. 1.— Morphological evolution of a group, a cluster, and a disk galaxy in a group-cluster merger for the model with $M_\text{cl} = 2.0 \times 10^{14} \, M_\odot$, $M_\text{gr} = 5.0 \times 10^{13} \, M_\odot$, and $V_{\text{rel}} = 430 \, \text{km/s}$. Each frame measures 4.73 Mpc (35 kpc) for the upper (lower) panels, and the time, indicated in the upper left corner of each panel, is in units of Gyr. The group is assumed to enter the cluster from the right side in this figure. In the upper four panels, background dark matter components are shown in cyan for the cluster and in magenta for the group. A cross in each panel represents the position of the disk in the group for each time. In the lower four panels, stellar components (stars and new stars that are originally gaseous components and converted into stellar ones by star formation) and gaseous ones are shown in magenta and cyan, respectively. We here do not intend to display dark halo components of the disk in order to show more clearly the morphological evolution of disk components.

Fig. 2.— The time evolution of global star formation rate of a disk galaxy in group-cluster merging for the models with $V_{\text{rel}} = 430 \, \text{km/s}$ (magenta). Here star formation rate relative to that of an isolated disk is shown for each time. Accordingly this figure describes to what degree the star formation of the disk in group-cluster merging is enhanced in comparison with that of isolated disk evolution. The result of a disk galaxy within an isolated group with $M_\text{gr} = 5.0 \times 10^{13} \, M_\odot$ and that of a disk galaxy within an isolated cluster with $M_\text{cl} = 2.0 \times 10^{14} \, M_\odot$ are also shown in green and in cyan, respectively, in order that tidal effects of time-dependent gravitational field of group-cluster merging can be more clearly demonstrated to play a vital role in triggering a starburst. For these isolated group and cluster models, a spiral orbits the center of the isolated cluster (group) with the pericenter distance of 127 (80.1) kpc. As is shown in this figure, the rapidly changing tidal gravitational field in group-cluster merging can more greatly destabilize the spiral and trigger a stronger starburst than isolated group and cluster models.

Fig. 3.— Morphology of a group-cluster merger at the time $T = 3.4 \, \text{Gyr}$ in the model with $V_{\text{rel}} = 602 \, \text{km/s}$. Dark matter components of the cluster and those of the group are shown in cyan and in magenta, respectively. The frame of this figure measures 5.67 Mpc, and a cross represents the position of a disk galaxy initially within the group. Starburst galaxies (or post-starburst ones) are more likely to remain well outside the cluster and located within the diffusely distributed dark matter components of the destroyed group for $3.4 \leq T \leq 7.9 \, \text{Gyr}$ in this group-cluster merging with rather large initial relative velocity.