Origin of companion galaxies in QSO hosts

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ABSTRACT

Recent morphological studies of QSO host galaxies by the Hubble Space Telescope (HST) have revealed that a sizable fraction of QSO host galaxies possess close small companion galaxies. It is however not clear why and how these companion galaxies are physically associated with the activation of QSO nucleus and the formation of QSO hosts. We here demonstrate that QSO companion galaxies are tidally formed by a gas-rich major galaxy merger and then orbit the merger remnant, based on the results of numerical simulations which investigate both gas fueling to the central seed massive black holes in the merger and global morphological evolution of the merger. We furthermore suggest that some of companion galaxies tidally formed in a major merger can evolve eventually into small compact elliptical galaxies observed frequently in the present-day bright massive galaxies. Thus our numerical simulations not only clarify the origin of companion galaxies observed in low and intermediate redshift QSOs but also provide an evolutionary link between QSO companion galaxies and the present-day compact elliptical galaxies located in the vicinity of giant elliptical galaxies.

Subject headings: quasars: general– galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: interaction – galaxies: structure

1. Introduction

Since faint nebulosity around quasars was discovered (Matthews & Sandage 1963; Sandage & Miller 1966), morphological studies of QSO host galaxies have revealed the evolutionary link between the formation of QSO hosts and the activation of QSO nucleus (Hutchings et al. 1982; Malkan 1984; Margon, Downes, & Chanan 1984; Smith et al. 1986; Heckman et al. 1991). Photometric and spectroscopic studies of QSO hosts furthermore provided valuable clues to the nature of stellar populations of QSO host (MacKenty & Stockton 1984; Boronson, Perrson, & Oke 1985; Stockton & Rigeway 1991; Dunlop et al. 1993; McLeod & Rieke 1994). One of the most remarkable observational evidences is that galaxy interaction and merging can trigger the nuclear activities of QSOs (Stockton 1982; Hutchings & Campbell 1983; Stockton & Mackenty1983; Hutchings & Neff 1992; Bahcall et al. 1997). In particular, the recent high-resolution morphological studies of QSO host galaxies by the Hubble Space Telescope (HST) and large grand-based ones found that a sizable fraction of QSO hosts have close companion galaxies likely to be interacting or merging with the hosts (Bahcall et al. 1995; Disney et al 1995). Although these observational studies strongly suggest that close companion galaxies in QSO hosts play a vital role in triggering QSO activities (Bahcall et al. 1995), it is still theoretically unclear why QSO host galaxies so frequently have companions and how QSO activities are physically associated with the formation and the evolution of such companion galaxies.

In this Letter, we numerically investigate both gas fueling to the seed black holes located in the central part of two disks in a gas-rich merger and the morphological evolution of the merger in order to present a plausible interpretation on the origin of small companion galaxies frequently observed in QSO host galaxies. We here demonstrate that the observed QSO companion galaxies are formed in the outer part of strong tidal tails during gas-rich major galaxy merging and then become self-gravitating compact galaxies orbiting elliptical galaxies formed by merging. We furthermore demonstrate that such companion galaxies are located within a few tens kpc of elliptical galaxies when efficient gas fueling to the central seed QSO black holes continues. We thus suggest that both the formation of QSO companion galaxies and the activation of QSO nucleus result from one physical process of gas-rich major galaxy merging. We furthermore discuss whether such companion galaxies formed in QSO hosts can finally become compact elliptical galaxies that are frequently observed in the present-day bright massive galaxies.

2. Model

We construct models of galaxy mergers between gas-rich disk galaxies with equal mass by using Fall-Efstathiou model (1980). The total mass and the size of a progenitor disk are $M_{\rm d}$ and $R_{\rm d}$, respectively. From now on, all the mass and length are measured in units of $M_{\rm d}$ and $R_{\rm d}$, respectively, unless specified. Velocity and time are measured in units of $v = (GM_{\rm d}/R_{\rm d})^{1/2}$ and $t_{\rm dyn} = (R_{\rm d}^3/GM_{\rm d})^{1/2}$, respectively, where G is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_{\rm d} = 6.0 \times 10^{10}$ $\rm M_{\odot}$ and $R_{\rm d} = 17.5$ kpc as a fiducial value, then $v = 1.21 \times 10^2$ km/s and $t_{\rm dyn} = 1.41 \times 10^8$ yr, respectively. In the present model, the rotation curve becomes nearly flat at 0.35 $R_{\rm d}$ with the maximum rotational velocity $v_{\rm m} = 1.8$ in our units. The corresponding total mass $M_{\rm t}$ and halo mass $M_{\rm h}$ are 5.0 and 4.0 in our units, respectively. The radial (R) and vertical (Z) density profile of a disk are assumed to be proportional to $\exp(-R/R_0)$ with scale length $R_0 = 0.2$ and to $\mathrm{sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.04$ in our units, respectively. The Toomre's parameter (Binney & Tremaine 1987) for the initial disks is set to be 1.2. The collisional and dissipative nature of the interstellar medium is modeled by the sticky particle method (Schwarz 1981). Star formation is modeled by converting the collisional gas particles into collisionless new stellar particles according to the Schmidt law (Schmidt

1959) with the exponent of 2.0. The initial gas mass fraction ($f_{\rm g}$) is considered to be a free parameter ranging from 0.1 (corresponding to a gas poor disk) to 0.5 (a very gas-rich one). We here present the result of the model with $f_{\rm g} = 0.5$, because this model most clearly shows the typical behavior of QSO companion formation. The dependence of the details of QSO companion formation on $f_{\rm g}$ will be described by our future paper (Bekki 1999).

The orbital plane of a galaxy merger is assumed to be the same as xy plane and the initial distance between the center of mass of merger progenitor disks is 8.0 in our units (140 kpc). Two disks in the merger are assumed to encounter each other parabolically with the pericentric distance of 1.0 in our units (17.5 kpc). The intrinsic spin vector of one galaxy in a merger is exactly parallel with z axis whereas that of the other is tilted by 30° from z axis. The present study describes the QSO companion formation only for a nearly prograde-retrograde merger in which only one intrinsic spin vector of a merger progenitor galaxy is nearly parallel with orbital spin vector of the merger. The dependence of the details of QSO companion formation processes on the initial orbital configurations of galaxy mergers will be given by Bekki (1999). The number of particles used in a simulation is 20000 for dark halo components, 20000 for stellar ones, and 20000 for gaseous ones. All the calculations including the dissipative and dissipationless dynamics and star formation have been carried out on the GRAPE board (Sugimoto et al. 1990) at Astronomical Institute of Tohoku University. The parameter of gravitational softening is set to be fixed at 0.03 in all the simulations.

By using this merger model, we firstly investigate morphological and dynamical evolution of a gas-rich major galaxy merger with a particular emphasis on the formation of close small companions (dwarf-like galaxy) in the merger. Secondly, we investigate when and how QSO activities are triggered by major galaxy merging by counting total mass of interstellar gas accumulated within the central 100 pc of a galaxy merger. In order to estimate the gas mass in a explicitly self-consistent manner, we initially place a collisionless particle with the mass equal to 3.0×10^6 in the mass center of a disk and regard this particle as a 'seed black hole'. We then investigate both the time evolution of the orbit of the seed black hole and the total gas mass transferred to the central 100 pc around the black hole. Here we hypothetically assume that interstellar gas transferred to the central 100 pc around the seed black hole can be furthermore fueled to the central sub-pc region where a massive black hole gravitationally dominates and utilizes gas falling onto the accretion disk for a QSO activity. The reason for our adopting this assumption is that we regard a certain mechanism for gas fueling to the sub-pc region, such as the so-called 'bars within bars' proposed by Shlosman, Frank, & Begelman (1989), as being occurred naturally in the high-density self-gravitating central regions of galaxy mergers. The above two-fold investigation just allows us to address questions as to when and how galaxy merging not only forms small companions but also triggers QSO nuclear activities.

EDITOR: PLACE FIGURE 1 HERE.

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3. Result

Figure 1 describes how a QSO companion galaxy is formed by gas-rich major galaxy merging. As two gas-rich disks merge to form a tidal tail composed of gas and stars (the time $T = 1.1$ Gyr), the stellar components in the tail first collapse to form a self-gravitating dwarf-like object. Gaseous components are then swept into the deep gravitational potential well of the dwarf galaxy to form a massive gaseous clump owing to the enhanced gaseous dissipation in the shocked region of the tidal tail and the dwarf. Star formation proceeds very efficiently in the high density gas clump, and consequently new stellar components are formed in the dwarf galaxy (T = 1.7 Gyr). The physical processes of the dwarf galaxy formation in the present star-forming galaxy merger are essentially the same as those described by Barnes & Hernquist (1992). This self-gravitating dwarf galaxy can then orbit an elliptical galaxy formed by galaxy merging without significant radial orbital decay due to dynamical friction between the dwarf and the host elliptical and tidal destruction by the elliptical (T = 2.3 and 2.8 Gyr). Total mass in the dwarf at T = 2.3 Gyr is roughly estimated to be $\sim 2.7 \times 10^9 M_{\odot}$ corresponding to 4.5 % of the initial disk mass. The gas mass fraction of the dwarf is rather large ($\sim$ 25%), which reflects the fact of the dwarf's being formed in the gas-rich tidal tail. About 45 % of stellar components of the dwarf are very young stars formed from gaseous components of the tidal tail, which implies that this dwarf galaxy can be observed to show very blue colors until its hot and massive stars died out. Considering that the present gas-rich star-forming merger model also shows efficient gas fueling to the central seed black holes (as is described later), we regard the above results as demonstrating clearly that the dwarf galaxy formed in galaxy merging can be observed as a companion galaxy in a QSO host galaxy.

Figure 2 shows the star formation history of the merger and the time evolution of gas mass located within the central 100pc around the seed black holes of the merger. Star formation rate becomes maximum ($\sim 378 M_{\odot}$/yr) at T = 1.3 Gyr, when two disks finally merge to form an elliptical galaxy and the efficient redistribution of angular momentum and gaseous dissipation by cloud-cloud collisions cooperate to form the extremely high-density gaseous regions in the central part of the merger. After the intense secondary starburst, the star formation then rapidly declines owing to the efficient gas consumption by the starburst. Gas fueling to the central seed black holes becomes maximum ($6.5 \times 10^8 M_{\odot}$) at T = 1.3 Gyr, which is the same as the maximum starburst of the merger. Gas supply for the seed black holes is greatly controlled by the rapid gas consumption by star formation, and consequently gas fueling gradually declines after the completion of the secondary starburst. The gas fueling in the present study tends to be more efficient in the late phase of galaxy merging ($T > 1.3$ Gyr) than in the early one ($T < 1.3$ Gyr). Assuming that all of the gas transferred to the central 100pc around the seed black holes can be directly accreted onto the accretion disk of the black holes, we can estimate that the mean accretion rate in the merger late phase (1.3 Gyr $< T <$ 2.3 Gyr) is $6.3 \mathrm{M}_{\odot}$/yr. The derived accretion rate is sufficient enough to trigger the typical magnitude of QSO activity (e.g., Rees 1984). These results imply that secondary massive starburst and QSO nuclear activity (AGN) can be observed to coexist in a QSO host galaxy, which is consistent with the observational evidence that some of QSO host galaxies show very bluer colors and spectroscopic properties indicative of the past starburst (MacKenty & Stockton 1984; Boronson, Perrson, & Oke 1985; Stockton & Rigeway 1991).

Thus Figure 1 and 2 clearly demonstrate that gas-rich major galaxy merging not only contributes to the formation of a companion galaxy orbiting a merger remnant but also triggers QSO nuclear activities. Accordingly our numerical study can naturally explain why QSO host galaxies, some of which are actually observed to be ongoing mergers and elliptical galaxies (e.g., Bahcall et al. 1997), are more likely to have close small companion galaxies; This is essentially because both QSO host galaxies with pronounced nuclear activities and their companions result from *one* physical process of major galaxy merging. Our numerical studies furthermore provide the following three predictions on physical properties of QSO companions and hosts. First prediction is that the luminosity of a QSO companion galaxy is roughly proportional to that of the QSO host, principally because the mass of tidal debris that is a progenitor of a QSO companion depends strongly on the initial mass of a galaxy merger. Second is that a QSO companion has very young stellar population formed in secondary starburst of galaxy merging and thus shows photometric and spectroscopic properties indicative of starburst or post-starburst. Third is that not all of galaxy mergers can create QSO companions galaxies, essentially because nearly retrograde-retrograde mergers can not produce strong tidal tails indispensable for the formation of companion galaxies because of the weaker tidal perturbation of the mergers (The details of the physical conditions required for the formation of QSO companions will be described in Bekki (1999)). We suggest that future observational studies on the dependence of the luminosity-ratio of QSO hosts to QSO companions on QSO host luminosity, age and metallicity distribution of stellar populations of QSO companions, and the probability that QSO host galaxies have companion galaxies physically associated with them can verify the above three predictions and thereby can determine whether major galaxy merging is a really plausible model of QSO companion formation.

4. Discussion and Conclusion

The fate of QSO companion galaxies is an interesting problem of the present merger scenario of QSO companion formation. We here propose that some of the companions finally evolve into compact elliptical galaxies (cE) that have typical blue magnitude $M_{\rm B}$ ranging from -18 mag to -14 mag, truncated de Vaucouleurs luminosity profile, color-magnitude relation of giant ellipticals, typically solar-metallicity, and higher degree of global rotation (Faber 1973; Wirth & Gallagher 1984; Nieto & Prugniel 1987; Freedman 1989; Bender & Nieto 1990; Burkert 1994). The essential reason of this proposal is described as follows. Burkert (1994) numerically investigated the dynamical evolution of proto-galaxies experiencing an initial strong starburst and the subsequent violent relaxation in the tidal external gravitational field of a massive elliptical galaxy and revealed that the observed peculiar properties of cEs are due to the external tidal field around progenitor proto-galaxies of cEs. Burkert (1994) accordingly proposed a scenario in which satellite proto-galaxies revolving initially around a bright elliptical galaxy eventually form cEs after violent cold collapse and strong starburst around the galaxy. Although his model of cE formation is not directly related to physical processes of gas-rich major galaxy merging, the physical environment of cE formation in his model is very similar to that of gas-rich galaxy merging; Tidal debris collapses to form a self-gravitating small galaxy in the rapidly changing external gravitational field of two merging disk galaxies in the present study. Accordingly it is not unreasonable to consider that some of companion galaxies created in tidal tails finally become cEs orbiting elliptical galaxies formed by major galaxy merging. The observational fact that cEs exist almost exclusively as satellites of bright massive galaxies (Faber 1973; Burkert 1994) strengthens the validity of the proposed evolutionary link between QSO companions and cEs. Furthermore, the larger degree of global rotation in kinematics observed in cEs (e.g., Bender & Nieto 1990) seems to be consistent with the proposed scenario, since QSO companions are created in the tidal debris of rotationally supported disk galaxies in the scenario. The present numerical study unfortunately cannot investigate in detail structural and kinematical properties of companion galaxies formed in galaxy mergers because of very small particle number of the simulated companion (~ 800). Our future high resolution simulations with the total particle number of $\sim 10^7$ will enable us to compare the numerical results of structural, kinematical, and chemical properties of QSO companions formed in major mergers with observational ones of cEs located near giant ellipticals in an explicitly self-consistent manner and thereby answer the question as to the evolutionary link between intermediate and high redshift QSO companions and the present-day cEs.

The most important observational test to assess the validity of the proposed formation scenario of QSO companion galaxies is to investigate whether a QSO companion galaxy has younger stellar populations formed by secondary starburst and thus shows photometric and spectroscopic properties indicative of starburst or post-starburst. Canalizo & Stockton

(1997) recently investigated spectroscopic properties of companion galaxies in three QSOs (3CR 323.1, PG 1700+518, PKS 2135-147) and found that the spectra of a companion galaxy in QSO PG 1700+518 shows both strong Balmer absorption lines from a relatively young stellar population and Mg I b absorption feature and the 4000 Å break from an old stelar population. Stockton, Canalizo, & Close (1998) furthermore demonstrated that the time that has elapsed since the end of the most recent major starburst event in the companion of QSO PG 1700+518 is roughly 0.085 Gyr, based on the spectral energy distribution derived from adaptive-optics image in J and H band. These observational results on the post-starburst signature of QSO companions are consistent reasonably well with the proposed scenario which predicts that a QSO companion galaxy contains both relatively old stellar populations previously located in merger progenitor disks and very younger stellar populations formed in gas-rich tidal tails. Detailed spectroscopic studies of QSO companion galaxies, such as Canalizo & Stockton (1997) and Stockton, Canalizo, & Close (1998), have not been yet so accumulated. Future extensive spectroscopic studies of companions in each of intermediate and high redshift QSOs will clarify the age distribution of stellar populations of the companions and thus determine whether most of QSO companions are really formed in major galaxy mergers.

We conclude that gas-rich major galaxy merging can naturally explain the prevalence of small companion galaxies in QSO hosts; The essential reason for the origin of QSO companions is that strong tidal gravitational field of major galaxy merging both triggers the formation of companions and provides efficient fuel for QSO nuclear activities. This explanation of QSO companion formation is consistent reasonably well with the observational fact that QSO nucleus are already activated though the companions are still located in the vicinity of the QSO hosts ($\sim$ a few tens kpc from the center of the hosts). Our numerical simulations accordingly suggest that the observed companion galaxies in QSO hosts are not the direct *cause* of QSO nuclear activities but the *result* of gas-rich major galaxy merging. Although minor galaxy merging between small companion galaxies and giant elliptical galaxies or disk ones is demonstrated to be closely associated with secondary massive starburst in disks (Mihos & Hernquist 1995) and strong starburst in shell galaxies (Hernquist & Weil 1992), the present study implies that this minor merging is probably less important in the activation of QSO nucleus and the formation of QSO companions. The present study provides only one scenario of QSO companion formation, thus we lastly stress that physical processes related to the companion formation are likely to be more variously different and complicated than is described in the present study.

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Fig. 1.— The morphological evolution of a major galaxy merger between two gas-rich, bulgeless spirals with star formation projected onto the x-y plane. In order to show more clearly the morphological evolution of disk components, we do not display the halo components here. Each frame measures 236 kpc (the scale is measured in units of 17.5 kpc), and the time, indicated in the upper left-hand corner of each panel is in units of gigayears. Note that the simulated morphology at $T = 1.1$ Gyr and that at $T = 2.8$ Gyr are remarkably similar to the QSO 1403+434 (Hutchings & Morris 1995) which is observed to have a dwarf-like companion galaxy *within* a tidal tail associated with the QSO and to the intermediate redshift QSO PKS2128-123 (Disney et al. 1995) which is observed to have a close compact companion around the well relaxed elliptical host galaxy, respectively.

Fig. 2.— The time evolution of the star formation rate (upper panel) and that of the total gas mass transferred to the central 100 pc of the seed black holes in a merger (lower panel). Note that both the star formation rate and the central gas mass become maximum at $T = 1.3$ Gyr.