SUBMITTED TO THE ASTROPHYSICAL JOURNAL LETTERS
Preprint typeset using LaTeX style emulateapj v. 9/08/03

BLACK HOLES IN GALAXY MERGERS: THE FORMATION OF RED ELLIPTICAL GALAXIES

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Submitted to the Astrophysical Journal Letters

ABSTRACT

We use hydrodynamical simulations to study the color transformations induced by star formation and active galactic nuclei (AGN) during major mergers of spiral galaxies. Our modeling accounts for radiative cooling, star formation, and supernova feedback. Moreover, we include a treatment of accretion onto supermassive black holes embedded in the nuclei of the merging galaxies. We assume that a small fraction of the bolometric luminosity of an accreting black hole couples thermally to surrounding gas, providing a feedback mechanism that regulates its growth. The encounter and coalescence of the galaxies triggers nuclear gas inflow which fuels both a powerful starburst and strong black hole accretion. Comparing simulations with and without black holes, we show that AGN feedback can quench star formation and accretion on a short timescale, particularly in large galaxies where the black holes can drive powerful winds once they become sufficiently massive. The color evolution of the remnant differs markedly between mergers with and without central black holes. Without AGN, gas-rich mergers lead to ellipticals which remain blue owing to residual star formation, even after more than 7 Gyrs have elapsed. In contrast, mergers with black holes produce ellipticals that redden much faster, an effect that is more pronounced in massive remnants where a nearly complete termination of star formation occurs, allowing them to redden to $u-r \simeq 2.3$ in less than one Gyr. AGN feedback may thus be required to explain the population of extremely red massive early type-galaxies, and it appears to be an important driver in generating the observed bimodal color distribution of galaxies in the Local Universe.

Subject headings: galaxies: formation — cosmology: theory — methods: numerical

1. INTRODUCTION

In hierarchical theories of galaxy formation, large systems are built up from mergers of smaller progenitors. Direct support for this picture comes from interacting pairs of galaxies seen in the Local Universe (Toomre & Toomre 1972). Fully self-consistent numerical models have demonstrated that interactions and mergers of spiral galaxies can produce remnants with properties similar to large elliptical galaxies (e.g. Barnes 1988, 1992; Hernquist 1992, 1993), as expected according to the "merger hypothesis" (Toomre 1977).

However, it is still controversial whether the merger scenario can account for detailed properties of the local galaxy population. For example, from large surveys like SDSS, 2dF-GRS or DEEP, it has been shown that the color distribution at fixed luminosity is bimodal (e.g. Strateva et al. 2001; Blanton et al. 2003; Kauffmann et al. 2003a), and can be well fitted by two Gaussians (e.g. Baldry et al. 2004). The mean and variance of these two distributions depend on luminosity, but surprisingly little on galaxy environment (Balogh et al. 2004). Also, there exists a population of massive, very red galaxies even at high redshift (e.g. Franx et al. 2003), which has been interpreted as evidence for monolithic galaxy formation at early times, rather than a more gradual build-up by a sequence of mergers.

If mergers of galaxies indeed produce red ellipticals from blue, star-forming disks, the color must be transformed from red to blue on a relatively short timescale, otherwise the 'gap' between the blue and red distributions would be washed out. The most straightforward way to achieve a rapid reddening of an elliptical would be for star formation to terminate abruptly following a merger, as could be the case, for example, if all the gas were consumed in a starburst.

It is, however, unclear whether merger-induced starbursts necessarily consume all the available gas, particularly in gas-rich mergers at high redshift. If they fail to do so and a small fraction of the gas remains, even a relatively low level of star formation in the remnant will prevent it from reaching the extremely red colors characteristic of many ellipticals. Instead, the residual star formation would decline slowly over a Hubble time (e.g. Mihos & Hernquist 1994, 1996; Hernquist & Mihos 1995), and the remnant would make a gradual transition into the red population that would blur the observational distinction between red and blue galaxies.

Here, we use hydrodynamical simulations of gas-rich mergers without AGN feedback to show that they do not necessarily produce remnants that are extremely gas-poor, even if a powerful starburst consumes a substantial fraction of the gas. Consequently, the color of the remnants does not evolve sufficiently rapidly to be consistent with the mean of the red population of the observed bimodal color distribution.

The situation is very different when the impact of central AGN in the merging galaxies is included. In recent years, a remarkable connection between galaxy formation and supermassive black holes has been revealed, indicating that their growth is linked. Perhaps the most direct evidence for this is the correlation seen between the stellar velocity dispersion of bulges and the masses of the black holes they host (e.g. Tremaine et al. 2002). Theoretical models conjecture that the correlation arises because black hole growth stalls once the energy deposition associated with the accretion can expel the remaining gas from the halo or bulge (Ciotti & Ostriker 1997, 2001; Silk & Rees 1998; Wyithe & Loeb 2003). This would also have an immediate bearing on star formation in the galaxy. In our simulations we include black hole accretion and feedback to examine their impact on star formation during galaxy mergers, focusing on the color evolution of the ensuing ellipticals. Our results demonstrate that these processes can quench star formation in large merger remnants, and that ellipticals formed in this manner redden sufficiently rapidly to

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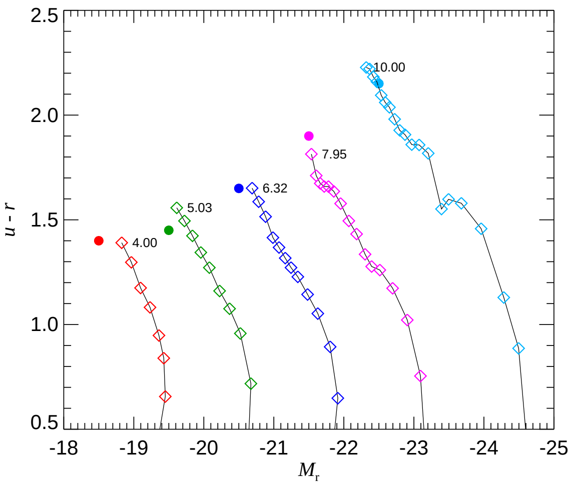

FIG. 1.— Evolutionary tracks of isolated, star-forming spiral galaxies initially with pure gas disks, in the color-magnitude plane of $u-r$ vs. M_r. From left to right, are models with $V_{\rm vir}$ = 80, 113, 160, 226, and 320 km s^{-1}. Diamonds on each track are spaced 0.5 Gyrs apart, and the age of the last point is labeled. Filled circles show the mean color of the blue part of the observed bimodal color distribution at a given luminosity (Balogh et al. 2004).

explain the observed color bimodality of local galaxies.

2. NUMERICAL SIMULATIONS

Our simulations were performed with GADGET-2, a new version of the parallel TreeSPH code GADGET (Springel et al. 2001). It uses an entropy-conserving formulation of SPH (Springel & Hernquist 2002), and includes radiative cooling, heating by a UV background, and a sub-resolution model of the multiphase structure of dense gas to describe star formation and supernova feedback (Springel & Hernquist 2003).

We have incorporated a novel procedure for handling accretion onto supermassive black holes (BHs) into this code. Briefly, we represent BHs by "sink" particles that accrete gas from their local environment. The accretion rate $\dot{M}_{\rm B}$ is estimated from the local gas density and sound speed, using a Bondi-Hoyle-Lyttleton parameterization together with an imposed upper bound equal to the Eddington rate. We further assume that a small fraction of 5% of the bolometric luminosity of $0.1\dot{M}_{\rm B}c^2$ (for an accretion efficiency of 10%) can couple dynamically to the ambient gas around the accreting black hole. This source of feedback is injected as thermal energy into the gas around the BH particle. A full discussion of our methodology is given in Springel, Di Matteo & Hernquist (2004). See also the recent studies by Kawata & Gibson (2004), who investigated a thermal AGN heating model not coupled directly to accretion, and by Kazantzidis et al. (2004), who followed completely 'passive' black hole particles in galaxy mergers.

Note that we do not attempt to resolve the small-scale accretion dynamics near the black hole; i.e. the complex processes that are ultimately responsible for transporting gas down to the last stable orbit. Instead, our modeling is based on the assumption that the time-averaged accretion, and feedback associated with the accretion, can be estimated from properties of the gas on scales ~ 100 pc, similar to our spatial resolution.

We generate stable, isolated disk galaxies using the approach outlined in Springel et al. (2004). Each galaxy has an extended dark matter halo with a profile motivated by cosmological simulations, an exponential disk of gas and stars, and a bulge. Here, we focus on only one particular choice for the structural properties of our disk galaxies, noting that our results are relatively insensitive to the details of these choices. We do, however, consider various galaxy masses, yielding a family of self-similar disk galaxy models with virial velocities $V_{\rm vir}$ = 80, 113, 160, 226, and 320 km s^{-1}. The total mass of each galaxy is $M_{\rm vir} = V_{\rm vir}^3/(10GH_0)$, with the baryonic disk having a mass fraction of $m_{\rm d} = 0.041$, the bulge of $m_{\rm b} = 0.0136$, and the rest being dark matter. The scale length of the disk is computed based on an assumed spin parameter of $\lambda = 0.041$, and the scale-length of the bulge set to 0.2 times the resulting disk scale-length. For a fiducial choice of $V_{\rm vir}$ = 160 km s^{-1}, the rotation curve and mass of the resulting model galaxy is similar to the Milky Way. Note that without the scale-dependent physics of cooling, star formation and black hole accretion, these galaxies would evolve in a self-similar fashion.

We eliminate the initial gas fraction of the disks as a separate free parameter by starting our simulations with pure gaseous disks. We here take advantage of the ability of our sub-resolution model for the star-forming gas to stably evolve even massive gaseous disks. This also avoids the need to specify an age distribution for disk stars that may already be present initially. In our default models, we use 168000 particles for the dark matter halo, 8000 particles for the bulge, 24000 particles for the gaseous disk, and one black hole sink particle, if present. The latter is given an initial seed mass of $10^5\,{\rm M}_\odot$ in all simulations. With this choice, the dark matter particles, gas particles, and star particles are all roughly of equal mass, and the central cusps in the profiles for the dark matter and bulge (Hernquist 1990) are reasonably well resolved. To check numerical convergence, we have also run a few of our simulations with eight times as many particles, where each galaxy model has 1.5 million particles in total.

We have carried out two different types of simulations. In our first set of runs, we evolved the galaxies in isolation to study how the gas disks are turned into stars, providing a simple model for the color evolution of quiescent, star-forming disk galaxies. In a second set, we have used pairs of the same models and set them on a collision course, with zero orbital energy and a small pericenter separation of 7.1 kpc (for the $V_{\rm vir}$ = 160 km s^{-1} case). By varying the initial separation in some of our mergers, we have also changed the time until the first encounter of the galaxies, and hence effectively modified the gas fraction in the galaxies when they coalesce. In the simulations analyzed here we only consider pure prograde encounters, for simplicity. However, we have checked with further simulations of more general encounters, where the disk spin vectors were tilted relative to the orbital plane, that our results are insensitive to the orbital configuration.

3. RESULTS

3.1. *Color evolution of isolated disk galaxies*

In Figure 1, we show evolutionary tracks of isolated, star-forming spiral galaxies in the color-magnitude plane of $u-r$ vs. M_r. We use the stellar population synthesis models of Bruzual & Charlot (2003) to compute rest-frame magnitudes in the SDSS bands for the simulated galaxies, assuming solar metallicity and a Chabrier initial mass function. We do not add corrections for internal extinction in the galaxies.

The galaxies start with pure gaseous disks, which are transformed into stellar disks on roughly an exponential timescale. The more massive galaxies shown in Figure 1 have some-

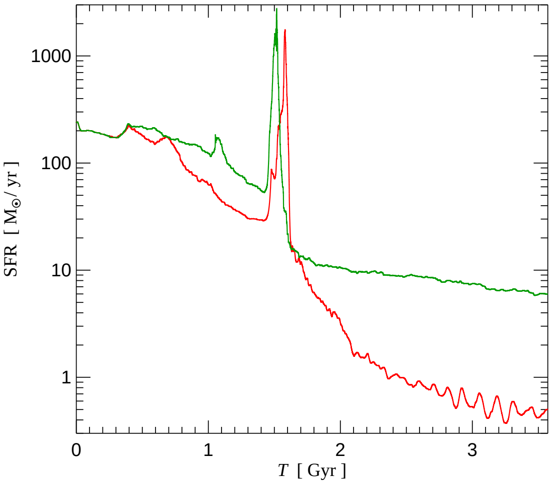

FIG. 2.— Comparison of the star formation rate history of two colliding gas-rich spirals of mass $3.85 \times 10^{12}\,\mathrm{M}_\odot$ with (red line) and without (green line) central supermassive BHs. The merger triggers a powerful starburst at time $\sim 1.5\,$Gyr, which is accompanied by a phase of Eddington accretion in the simulation with BHs. The feedback energy from accretion eventually blows away the gas surrounding the black holes, nearly terminating star formation in the remnant and stalling further growth of the black holes.

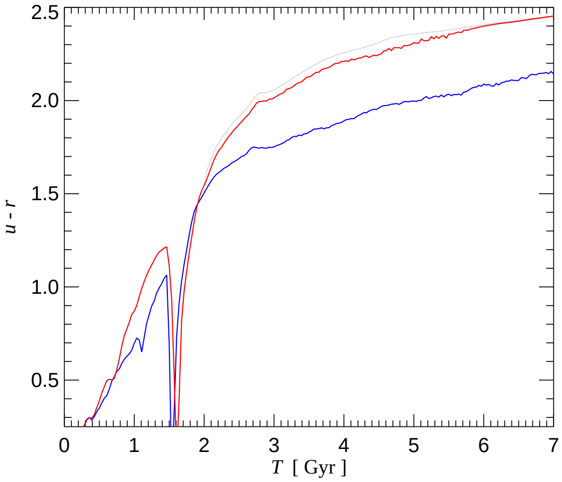

FIG. 3.— Comparison of the color evolution of the merger of two colliding gas-rich spirals of mass $3.85 \times 10^{12}\,\mathrm{M}_\odot$ ($V_{\rm vir} = 226\,\mathrm{km\,s^{-1}}$) with (red line) and without (blue line) central supermassive BHs. The thin gray line marks a fiducial color evolution assuming that no stars are formed after $T = 2\,$Gyr.

what shorter gas consumption timescales than less massive ones, as expected from the density-dependence of the assumed Schmidt-like star formation law (Springel & Hernquist 2003). This makes them slightly redder at the same age. However, to reproduce the strong trend with luminosity seen in the mean color of the blue population of star-forming galaxies (Balogh et al. 2004), one needs to assume that larger galaxies are also older. Formally, we obtain a good match to the observed trend if galaxies of total mass $\sim 4 \times 10^{12}\,\mathrm{M}_\odot$ started forming their stars about 4 Gyr earlier than galaxies of mass $\sim 10^{11}\,\mathrm{M}_\odot$. While this trend qualitatively agrees with the proposed notion of 'cosmic down-sizing' of star formation (Cowie et al. 1996; Kauffmann et al. 2003b), it is important to note that our isolated systems represent at best a crude model for disk formation because several cosmological effects are neglected, most notably infall. The results therefore primarily serve to illustrate the color evolution of our galaxies when they do not suffer a merger.

3.2. *Star formation and color evolution in mergers*

In Figure 2, we compare the star formation rates in collisions between two large gas-rich spirals, with and without black holes. The collision causes a nuclear inflow of gas, triggering a strong starburst, and fueling black hole accretion in the simulation with AGN. The feedback resulting from accretion first only damps the starburst, but once the black hole has accreted at its Eddington rate for several Salpeter times, it begins to drive a powerful quasar outflow. This wind can remove much of the gas from the inner regions of the merging galaxies, thereby nearly terminating star formation on a short timescale. As a result, there is almost no residual star formation in the remnant with black holes, as opposed to the ordinary simulation where the remnant keeps forming stars at a non-negligible rate of a few $\mathrm{M}_\odot/\mathrm{yr}$ for several Gyr. An analysis of the dynamics and the final masses of the BHs in these simulations is given in Di Matteo et al. (2004).

In Figure 3, we compare the temporal evolution of the $u-r$ color in these two merger simulations. After a brief excursion into the extreme blue during the bursts, when much of the gas is consumed, both remnants begin to redden. However, this happens substantially faster when AGN feedback is included. In fact, in our simulation set we find that for galaxies more massive than $\sim 3 \times 10^{12}\,\mathrm{M}_\odot$ the color evolution of the remnants is consistent with one where no stars are formed *at all* after the burst – they will hence quickly evolve into extremely red, massive elliptical galaxies.

However, we note that the magnitude of this "termination effect" depends on the masses of the galaxies involved. Because the BHs in small galaxies grow only relatively little in mass, consistent with the $M_{\rm B}-\sigma$ relation, AGN feedback is much less efficient in smaller galaxies. Consequently, the change in the remnant evolution is progressively weaker for less massive galaxies. In the smallest galaxies we considered, of virial velocity $V_{\rm vir} = 80\,\mathrm{km\,s^{-1}}$, the color evolution is nearly unchanged between simulations with and without black holes. In mergers of these systems, the small spheroidal galaxies that form remain relatively gas-rich and exhibit ongoing star formation. Such galaxies appear to exist. For example, using data from the DEEP survey of the Groth strip, Im et al. (2001) show that a substantial fraction of morphologically selected early-type galaxies at $z \leq 1$ have blue colors, and that they are likely to be low-mass, star-forming spheroids.

3.3. *Relation to the bimodal color distribution*

In Figure 4, we show evolutionary tracks of the color evolution of the merger simulations for different progenitor masses, again in the $u-r$ vs. M_r plane. The last points on the tracks correspond to an age of $\sim$ 5.5 Gyr after the merger-induced starbursts. At this fiducial time, we compare to the mean color of the red part of the bimodal color distribution in the Local Universe, as determined by Balogh et al. (2004) for the SDSS.

The large spacings of the markers on the track of the massive disk galaxies during the transition from blue to red illustrate how rapidly the color transformation proceeds. Already $\sim$ 1 Gyr after the merger, the color has reddened to about $u-r \simeq 2.0$, and after a further Gyr, it reaches about $u-r \simeq 2.2$. In contrast, without black holes the remnant takes

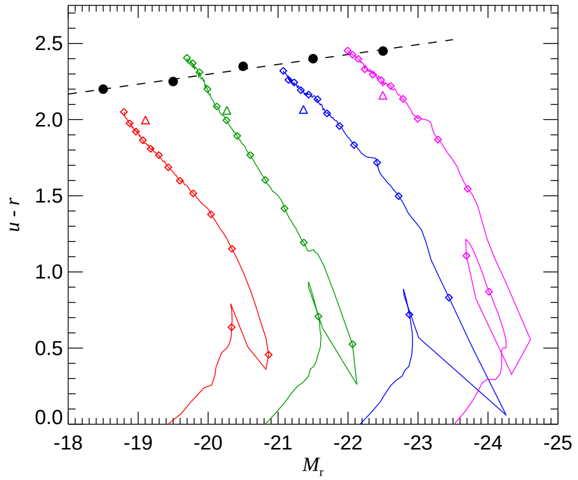

FIG. 4.— Color evolution in the $u-r$ vs. M_r plane for gas-rich mergers with black hole accretion. Symbols on the tracks are spaced 0.5 Gyr apart, with the last point corresponding to an age of $\sim$ 5.5 Gyr after the merger-induced starburst. For comparison, triangles show mergers without black holes at the same time, and the solid circles give the observed mean color of the red part of the bimodal color distribution at a given luminosity (Balogh et al. 2004).

5.5 Gyr to reach $u-r \simeq 2.1$, and has difficulty reaching the observed redness even after a Hubble time.

This result also demonstrates an important connection to the observed bimodal color distribution of galaxies. AGN feedback appears to be required in order to move galaxies from the blue star-forming population into the red population of "dead" galaxies sufficiently rapidly. If the transition is too slow, there should be many more galaxies with intermediate colors, which would wash out the observed bimodality. Interestingly, the observed trend with luminosity of the mean color of the red mode of the bimodal color distribution can be approximately reproduced by our merger remnants with BHs, at a time roughly 5.5 Gyr after completion of the mergers. As a look-back time, this would correspond to a formation redshift of $z \simeq 0.7$. Without black holes, the galaxies reach the required redness only much later, or not at all within a Hubble time. While the idealized nature of our individual galaxy mergers preclude us from drawing definite statistical conclusions, our results indicate that BH feedback is essential for shaping the bimodal color distribution of galaxies.

4. CONCLUSIONS

We have demonstrated that gas-rich galaxies do not necessarily consume all their gas in the starbursts that accompany major mergers. Consequently, ellipticals formed in such events can sustain star formation for extended periods of many Gyrs that makes them relatively blue. However, if the merging galaxies host supermassive black holes at their centers, AGN feedback provides a mechanism to quench star formation on a short timescale. This introduces a marked difference in the color evolution of galaxies: mergers of massive galaxies can produce remnants that redden to $u-r \simeq 2.2-2.3$ in about $1-2$ Gyrs. Moreover, the AGN feedback drives a gaseous outflow which leaves behind a gas-poor remnant. The "dead" ellipticals formed in this manner should be a good match to the luminous red stellar populations of many massive ellipticals, which are devoid of star-forming gas and lack young stars. Also, AGN feedback may be an important driver in shaping the observed bimodal color distribution of galaxies.

Because black hole growth is a strong function of the size of the spheroid formed, the effects of AGN feedback sensitively depend on the masses of the merging galaxies. In our simulations, black hole accretion modifies the properties of large elliptical remnants strongly, while those of forming dwarf spheroidal systems are largely unaffected.

It is now widely believed that the formation of spheroids and the growth of supermassive black holes are intimately linked. If this is the case, then black holes should not be ignored in models of galaxy formation, since even basic properties like the color of ellipticals can be influenced strongly by them, as we have shown here. Hydrodynamical simulations of galaxy formation that self-consistently account for star formation and the growth of black holes promise to be an important tool for exploring this connection further, which may well lead to fundamental changes in the theory of hierarchical galaxy formation.

This work was supported in part by NSF grants ACI 96-19019, AST 00-71019, AST 02-06299, and AST 03-07690, and NASA ATP grants NAG5-12140, NAG5-13292, and NAG5-13381. The simulations were performed at the Center for Parallel Astrophysical Computing at the Harvard-Smithsonian Center for Astrophysics.

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