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# FORMATION OF A SPIRAL GALAXY IN A MAJOR MERGER

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## ABSTRACT

We use numerical simulations to examine the structure of merger remnants resulting from collisions of gas-rich spiral galaxies. When the gas fraction of the progenitors is small, the remnants structurally and kinematically resemble elliptical galaxies, in agreement with earlier work. However, if the progenitor disks are gas-dominated, new types of outcomes are possible. In fact, we show that a prominent disk may survive in certain cases. To illustrate this scenario, we analyze an extreme example with progenitor galaxies consisting of dark matter halos, pure gas disks, and no bulges, as might be appropriate for mergers at high redshifts. While rapid star formation triggered by tidal torques during the merger forms a central, rotating bulge in the remnant, not all the gas is consumed in the burst. The remaining gas cools very quickly and settles into an extended star-forming disk, yielding an object similar to a spiral galaxy, and *not* an early type galaxy. This is contrary to the usual view that major mergers invariably destroy disks. The morphological evolution of galaxies can therefore be more complicated than often assumed, and in particular, theoretical constraints based on the fragility of spiral disks need to be reevaluated.

*Subject headings:* galaxies: structure – galaxies: interactions – galaxies: active – galaxies: starburst – methods: numerical

## 1. INTRODUCTION

Mergers and interactions between galaxies are an essential ingredient to galaxy formation and evolution. The gravitational tidal forces associated with this process can explain the morphological characteristics of peculiar galaxies (Toomre & Toomre 1972), and it is believed that mergers can trigger the elevated levels of star formation seen in ultraluminous infrared galaxies (Sanders et al. 1988; Melnick & Mirabel 1990). Various observations suggest that quasars, radio galaxies, and active galactic nuclei (AGN) are formed in mergers (for reviews, see e.g. Barnes & Hernquist 1992; Jogee 2004). Moreover, according to hierarchical models of structure formation (White & Rees 1978), it is expected that galaxies grow with time through mergers.

Toomre (1977) was among the first to recognize that mergers can drive the evolution of galaxy types by transforming disks into objects that resemble ellipticals. This idea was examined numerically by Barnes (1988, 1992) and Hernquist (1992, 1993b) in the limit where dissipational effects arising from gas dynamics are negligible, and it was shown that mergers involving equal-mass galaxies (i.e. “major” mergers) do indeed yield remnants with properties similar to those of observed ellipticals. Simulations including gas dynamics and simple prescriptions for star formation and feedback have further demonstrated that major mergers can drive gas to the center of a remnant (Barnes & Hernquist 1991, 1996), triggering starbursts with intensities similar to those of observed ultraluminous infrared galaxies (Mihos & Hernquist 1996).

While major mergers are the most striking examples of galaxy collisions, “minor” mergers between galaxies of different masses are probably at least an order of magnitude more frequent (Ostriker & Tremaine 1975; Toomre 1981). Simulations have shown that dissipationless minor mergers between spiral galaxies and smaller companions can cause significant perturbations to disks through dynamical heating (Quinn & Goodman 1986; Quinn et al. 1993; Walker et al. 1996; Velazquez & White 1999). Even with large mass ratios $\sim 10:1$, the damage can be severe because disks of spirals are dynamically cold. This conclusion is unaffected by dissipation when the disks contain a small fraction ($\sim 10\%$) of their mass in gas (Hernquist 1989; Hernquist & Mihos 1995).

Together, the results for both major and minor mergers indicate that galaxy collisions are problematic for the long-term survivability of disks. Toth & Ostriker (1992) used this notion to constrain the cosmological merger rate by arguing that disks like that of the Milky Way would not survive to the present day if they were constantly bombarded by smaller companions, posing a challenge for hierarchical galaxy formation.

However, the argument put forward by Toth & Ostriker (1992) was based on theoretical models in which the interstellar gas was at most a small fraction of the disk mass. Previous numerical studies of minor mergers were restricted to cases where the gas fraction was low because of gravitational instabilities in isolated galaxies with cold, gas-dominated disks. The simulations of Hernquist (1989) and Hernquist & Mihos (1995), for example, employed disks with 10% gas because these authors described the interstellar medium (ISM) using an isothermal equation of state and they included only a minimal form of kinetic feedback from massive stars (Mihos & Hernquist 1994). This approach produces unstable models for much larger gas fractions.

Recently, Springel et al. (2004) have developed a method for constructing stable disks with arbitrary ratios of gas to stellar mass. Their approach employs a sub-resolution, multiphase model of the ISM that captures the impact of star formation and supernova feedback on resolved scales (Springel & Hernquist 2003a). While the “microscopic” structure of the ISM is not followed in detail in this methodology, the coarse-graining that is used to form a “macroscopic” representation of star formation describes the consequences of feedback in a simple and physical manner through an effective equation of state (EOS) for the star-forming gas. In

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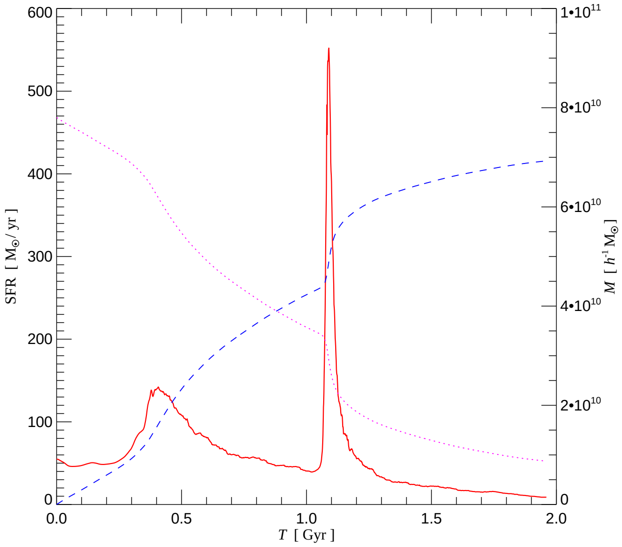

FIG. 1.— Evolution of the star formation rate and gas and stellar mass in a major merger of two disk galaxies without bulges. The disks of the galaxies initially consisted entirely of gas. The solid line shows the evolution of the star formation rate (left axis), while the dashed and dotted lines give the evolution of the total stellar and gas mass (right axis) of the galaxy pair.

this picture, feedback from star formation pressurizes the gas so that the effective EOS is stiffer at high densities than if the gas had been isothermal, stabilizing disks against fragmentation.

In what follows, we use the Springel et al. (2004) procedure to simulate major mergers between disk galaxies with large gas fractions. We demonstrate that a new type of outcome is possible when the modeling is extended to cases where the galaxies are very gas-rich, as might be appropriate for systems at high redshifts. In particular, we find that if sufficient gas remains following a major merger, cooling can quickly reform a disk, yielding a remnant that, structurally and kinematically, more closely resembles a spiral galaxy than an elliptical. This outcome is contrary to the usual view that mergers invariably destroy disks. Clearly, the issue of disk survival in a hierarchically evolving universe needs to be reexamined in the context of our models.

## 2. METHODOLOGY

In Springel et al. (2004), we constructed near-equilibrium galaxy models consisting of dark matter halos, disks of gas and stars, and optional bulges, using a procedure developed by Hernquist (1993a) and Springel (2000), but with a number of refinements. The dark matter follows a Hernquist (1990) profile, scaled to match the inner density distribution of halos found in cosmological simulations (Navarro et al. 1996). The disks have exponential surface densities in both the stars and gas, with the vertical gas profile determined self-consistently for a particular EOS. Star formation is described using a sub-resolution model of the ISM (Springel & Hernquist 2003a) to describe the star-forming gas as a multiphase medium whose structure is regulated by gas cooling, supernova feedback, and thermal evaporation of cold clouds. We have also implemented schemes to include supernova-driven winds (Springel & Hernquist 2003a) and feedback from black-hole accretion (Springel et al. 2004), but we ignore these effects here.

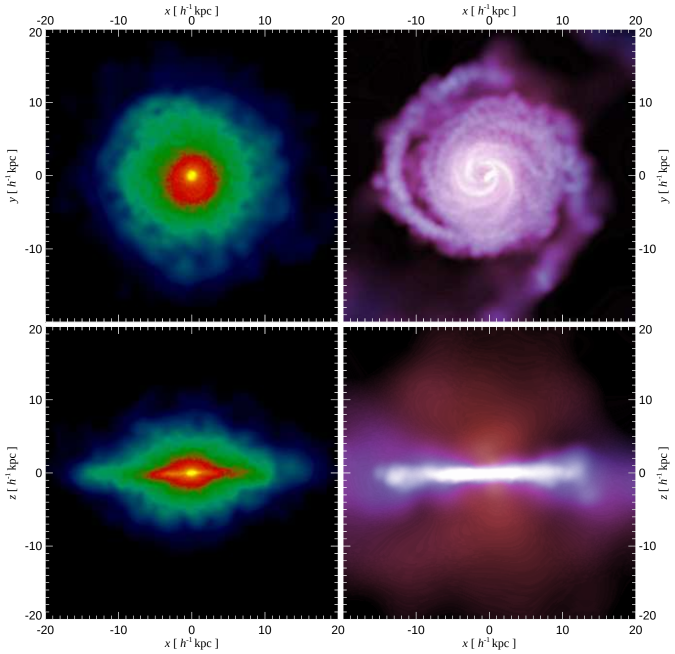

FIG. 2.— Distribution of stars (left panels) and gas (right panels) following the completion of the merger at a time $t$ = 1.96 Gyr, when the inner parts of the remnant have relaxed. The top panels show a face-on view of the remnant disk, while the bottom panels are edge-on.

In a parameter study carried out in Springel et al. (2004), we have run a suite of models of both isolated and merging galaxies, varying the structural properties of the galaxies, the strength of supernova feedback, the gas fraction of the disks, and the orbit (for collisions). In this paper, we focus on one specific case to illustrate an interesting new type of outcome that is possible when highly gas-rich disks merge. The simulation we analyze follows a major merger of two equal mass galaxies from a prograde, parabolic orbit. Initially, each galaxy consisted of a dark matter halo of mass $M = 9.13 \times 10^{11}\,h^{-1}\mathrm{M}_\odot$, and an exponential disk of pure gas with mass $M = 3.90 \times 10^{10}\,h^{-1}\mathrm{M}_\odot$. Neither galaxy began with a stellar bulge component. We choose to concentrate on this example to simplify the discussion, but our conclusions are not restricted to the parameters specifying the galaxies or the orbit, provided that the disks are significantly more gas-rich than in the earlier work of Barnes & Hernquist (1991, 1996) and Mihos & Hernquist (1996). For modeling star formation and feedback, we have used the formalism of Springel & Hernquist (2003b), but we softened the equation of state (EOS) with a factor $q_{\mathrm{EOS}} = 0.5$ (as discussed by Springel et al. 2004), so that the effective pressure at densities above the star formation threshold is midway between an isothermal EOS and our full, "stiff" multiphase model. In isolation, the model galaxies for this choice of $q_{\mathrm{EOS}}$ are stable and form stars at a steady rate owing to the pressurization of the gas from star formation, even though the disks are pure gas and the galaxies do not include bulges.

We used 120000 particles to represent the dark matter, and 80000 to represent the gas with SPH particles. We evolved the system over time with an improved and updated version of the simulation code GADGET (Springel et al. 2001), using a fully conservative formulation of SPH (Springel & Hernquist 2002) that maintains strict entropy and energy conservation even when smoothing lengths vary adaptively.

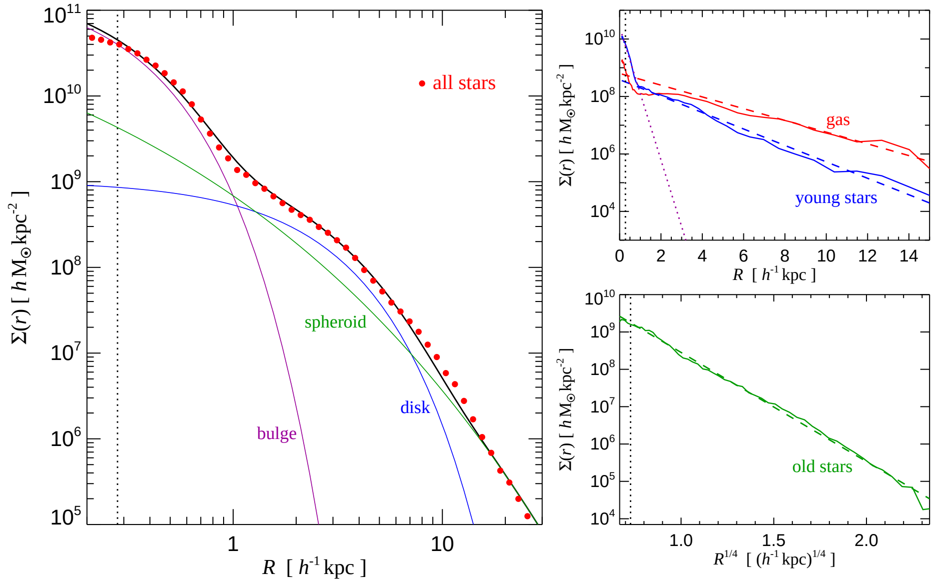

FIG. 3.— Surface mass density distribution of stars following the completion of the merger at a time $t = 1.96$ Gyr. The left panel shows the measurements for the total stellar density (symbols) together with a fit based on three components, a central bulge, an extended spheroid and an exponential stellar disk. The scale-lengths of these components are obtained by fitting stars of selected ages. 'Young' stars are well fitted by an exponential (top right panel), while 'old' stars in the remnant form a $r^{1/4}$ profile (bottom right panel). Dashed vertical lines mark the spatial resolution limit of the simulation.

## 3. RESULTS

In Figure 1, we show the evolution of the star formation rate and the total gas and stellar mass during the merger. The star formation rate in each disk prior to the encounter is relatively high, $\sim 20\,\mathrm{M}_\odot/\mathrm{yr}$, because of the high gas content of each galaxy. When the galaxies first pass by one another, near time $t \approx 0.4$ Gyr, a moderate burst of star formation is induced in each disk, owing to the tidal deformation experienced by each galaxy. A much stronger burst occurs during the final coalescence of the two galaxies, near $t \approx 1.1$ Gyr, reaching a peak amplitude $\simeq 550\,\mathrm{M}_\odot/\mathrm{yr}$. Following the completion of the merger, the remnant continues to form stars at a declining, but relatively steady rate $\sim 10\,\mathrm{M}_\odot/\mathrm{yr}$. Star formation rates at the level of $\approx 500\,\mathrm{M}_\odot/\mathrm{yr}$ are similar to those inferred for systems at high redshift such as Lyman-break galaxies and SCUBA sources, suggesting that some of these objects may result from mergers of gas-rich disks.

The evolution shown in Figure 1 is reminiscent of that seen by Mihos & Hernquist (1996), but with several differences, as can be seen by comparing the results here with the "Halo/Disk Merger" in their Figure 5a. The starbursts in our new simulations are much more intense than those found by Mihos & Hernquist (1996) owing to the the larger gas fractions of our new model galaxies. In addition, the first starburst in Figure 1 at $t \approx 0.4$ Gyr is weaker than that which follows during the late stages of the merger at $t \approx 1.1$ Gyr, unlike the behavior found by Mihos & Hernquist (1996) for their halo/disk mergers. This difference is a consequence of our treatment of feedback, which prevents the gas from being strongly compressed during the first encounter between the galaxies. This result demonstrates that the history of star formation predicted for galaxy mergers is sensitive to assumptions made in describing star formation. In the future, it may be possible to constrain these prescriptions by comparing the simulations with detailed observations, an approach being pioneered by e.g. Barnes (2004) for the Mice.

As shown in Figure 1, about half the gas initially in the galaxies is converted into stars before the intense starburst during the final merger. However, a substantial amount of gas is left over; consequently, the remnant is not purely stellar. Dissipation in the gas yields a remnant with a large, star-forming disk, owing to conservation of angular momentum. In Figure 2, we show the distribution of gas and stars in the remnant at $t = 1.96$ Gyr. A rotationally supported gaseous disk is seen in the merger remnant.

In Figure 3, we show an analysis of the stellar surface mass density profile of the remnant, as seen when looking onto the orbital plane. The profile can be quite well fitted with the sum of three physically motivated components. The first describes a central stellar bulge formed by the starbursts, the second an exponential stellar disk owing to ongoing star formation in the newly formed gas disk, and the third an extended stellar spheroid originating from the old disks destroyed during the collision. Looking at stars of different age allows a clear identification of these components. 'Young' stars, defined here as stars forming after $T = 1.2$ Gyr when the merger is approximately completed, are distributed in an exponential disk (top right panel). Note that the gas forms an exponential disk as well, with a scale length larger by a factor 1.4, as expected based on the Kennicutt law. If we consider 'old' stars instead, defined here as stars forming before the first burst at $T = 0.3$ Gyr, we find a nearly perfect $r^{1/4}$-profile (bottom right panel). We expect that a collisionless merger with pure stellar disks in the colliding galaxies would exhibit a very similar final profile. Finally, stars forming during the intense burst in the interval $1.05\,\mathrm{Gyr} \leq T \leq 1.2\,\mathrm{Gyr}$ are found in a centrally concentrated spheroid. This bulge can be fitted with a $r^{1/4}$-profile or with an exponential, with a slight preference for the latter.

For a decomposition of the total profile, we keep the scale lengths of the three components identified above fixed, and only vary their relative amplitudes. This decomposition (left panel) attributes 68% of the stars to the bulge component, 27% to the stellar disk, and 5% to the extended spheroid. Note

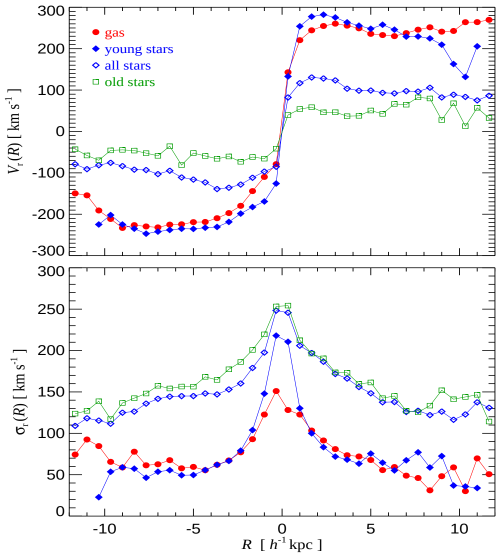

FIG. 4.— Kinematic profiles of the merger remnant. For a slit placed across the galaxy edge-on, we show the mean radial velocity (top panel), and the line-of-sight velocity dispersion (bottom panel). Different symbols are used for gas and star particles, and results for young ($T < 0.3\,$Gyr) and old stars ($T > 1.2\,$Gyr) are shown separately.

that these numbers bear some uncertainty owing to the near degeneracy of the disk and extended spheroid profiles. The corresponding half-mass radii are 0.3, 2.6 and $1.7\,h^{-1}$kpc, respectively. By coincidence, the mass of the remaining gas is almost the same as the disk mass. Most of this left-over gas is found in the disk, so that the stellar disk can be expected to almost double in mass within a few Gyrs, but it will not quite reach the mass of the bulge, unless there is cosmological infall of fresh gas. So the bulge, formed largely as a result of the two bursts, is likely to remain quite prominent in this galaxy.

Further information about the structure of the remnant can be obtained from kinematical data. In Fig. 4, we analyze the line-of-sight mean velocities and velocity dispersions across a slit placed edge-on over the remnant. Gas and young stars in the remnant are seen to be rotationally supported, while the old stars are predominantly dispersion supported, with small residual rotational support. We have also directly compared the azimuthal streaming velocities of gas and young stars with the rotation curve measured in the plane of the disk by differentiation of the potential. These curves agree very well, confirming the rotational support of these components.

## 4. DISCUSSION

Major mergers of disk galaxies play a prominent role in hierarchical models of galaxy formation. They are thought to be a primary path for the formation of large elliptical galaxies, and to give rise to powerful starbursts and AGN accretion events. Typically, semi-analytical models of galaxy formation make the simplifying assumption that the gas present in a major merger is completely consumed in a powerful burst, such that a spheroidal remnant without a disk component is formed.

The simulation we analyzed here provides a counter-example to this assumption, demonstrating that it cannot be correct in detail. We have shown that gas-rich mergers can still have a significant fraction of their gas left over after coalescence, despite the occurrence of powerful starbursts during the merger process. As a result, the remnant can quickly regrow a disk, such that the morphology of the stellar remnant is never really purely spheroidal, despite being the direct product of a major merger. This is at odds with traditional tenets about major mergers. The morphological evolution of galaxies in mergers can, therefore, be more complicated than previously assumed.

While we here focused on a particular galaxy collision with a favorable prograde orbit for disk formation, we note that our conclusions are not restricted to this special case. However, they do depend on the modeling of the ISM we adopted here. For simpler models of the ISM where feedback is ignored, we are unable to simulate disk galaxies as gas-rich as the ones considered here in a stable fashion for a sufficiently long time. Instead, the galaxies then quickly fragment and consume most of the gas before the collision takes place. This highlights the importance of the modeling of star formation and feedback processes for disk stability, and for theoretical arguments based on it (Toth & Ostriker 1992). If disks can "survive" even major mergers, they are probably less fragile than previously thought.

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