

# Forming a Large Disk Galaxy from a $z < 1$ Major Merger

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## ABSTRACT

Using high resolution SPH simulations in a fully cosmological  $\Lambda$ CDM context we study the formation of a bright disk dominated galaxy that originates from a “wet” major merger at  $z=0.8$ . The progenitors of the disk galaxy are themselves disk galaxies that formed from early major mergers between galaxies with blue colors. A substantial thin disk grows rapidly following the last major merger and the present day properties of the final remnant are typical of early type spiral galaxies, with an  $i$  band B/D  $\sim 0.65$ , a disk scale length of 7.2 kpc,  $g-r = 0.5$  mag, an HI line width ( $W_{20}/2$ ) of 238 km/sec and total magnitude  $i = -22.4$ . The key ingredients for the formation of a dominant stellar disk component after a major merger are: i) relative fading of the spheroidal component, ii) supernova feedback that is able to partially suppress star formation during mergers, iii) substantial and rapid accretion of gas through cold flows followed at late times by cooling of gas from the hot phase. The gas fraction of the progenitors’ disks does not exceed 25% at  $z < 3$ , emphasizing that the continuous supply of gas from the local environment plays a major role in the regrowth of disks and in keeping the galaxies blue. The results of this simulation alleviate the problem posed for the existence of disk galaxies by the high likelihood of interactions and mergers for galaxy sized halos at relatively low  $z$ .

**Key words:** galaxies: formation, evolution, interactions, methods: N-Body Simulations.

## 1 INTRODUCTION

Within the  $\Lambda$ CDM framework the build up of galaxies and their parent dark matter (DM) halos occurs through a series of mergers and accretion of more diffuse matter (Frenk et al. 1985; Springel & et. al. 2005). The classic models of galaxy formation (White & Rees 1978; Fall 1983; White & Frenk 1991) and subsequent work (Dalcanton et al. 1997; Mo et al. 1998; Silk 2001; Bower et al. 2006; Zheng & et al. 2007; Somerville et al. 2008) assume that gas infalls inside the parent dark matter halo and subsequently cools to temperatures low enough to fragment and form stars. The morphology of galaxies and the fraction of stars in their disk and spheroidal components are set by a combination of competing physical processes, as numerical simulations have shown that violent relaxation in mergers between similar size galaxies can destroy or dynamically heat their stellar disks and turn them into spheroids (Barnes & Hernquist 1996). On the other

hand, remaining and subsequently accreted gas can regrow a disk (Baugh et al. 1996; Steinmetz & Navarro 2002) if given enough time. It is then a prediction of hierarchical models that the morphology of a galaxy is not assigned “ab initio” but it might change often over cosmic times, as the spheroidal to disk light ratio changes back and forth. Observed merger remnants have disky isophotes (Rothberg & Joseph 2004) or evidence for young disk components (McDermid & et al. 2006), hinting at disk regrowth and supporting the above scenario.

Observationally, major mergers are observed to be common in the redshift range  $0 - 1$ . Their number density has been estimated to be of the order of  $10^{-(3-4)} h^{-1} \text{Mpc}^{-3} \text{Gyr}^{-1}$ , (Lin & et al. 2008; Jogee & et al. 2008), possibly increasing with redshift. As numerical work suggests that a consistent supply of gas is important to regrow a disk component (Robertson et al. 2006), it is relevant that observational evidence for mergers between actively star forming galaxies has also emerged, showing that at redshift  $\sim 1$ , 70% of the merging pairs are between blue (or “wet”, defined as rest frame

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g-r < 0.65) pairs; however the fraction of blue and likely gas rich mergers decreases by the present time (Lin & et al. 2008).

Numerical work has also highlighted a possible problem for the existence of disk galaxies at low redshift, showing that interactions, mergers and accretion events are common at every redshift for  $L^*$  galaxy sized halos in  $\Lambda$ CDM models (Maller et al. 2006; Stewart et al. 2008) and potentially destructive for disks (Toth & Ostriker 1992; Kazantzidis et al. 2007; Bullock et al. 2008; Purcell et al. 2008). This makes it potentially difficult to reconcile the observed present day population of disk dominated galaxies with  $\Lambda$ CDM, if a quiet merging history is essential for their existence. But do disk galaxies really require a quiet merging history to be observed as such at the present time? What are the time scales of disk growth and destruction? How quickly do disk galaxies regrow after a merger? Theoretical models also highlight the difficulties in predicting the outcomes of galaxy mergers and the subsequent regrowth of disks. These difficulties arise from several factors. Given the decoupling of the baryonic cores from the parent halos it is difficult to predict robust merging rates of galaxies (as compared to their DM halos) unless cosmological simulations with hydrodynamics are used (Maller et al. 2006). Also, numerical simulations have shown how the bulge to disk ratio (B/D) resulting from a major merger might depend on the orbital parameters, the internal spin of the progenitors, the gas fraction of the parent disks and the efficiency of SN feedback (Barnes & Hernquist 1996; Cox et al. 2006; Scannapieco et al. 2008).

Recent observational and theoretical work has pointed out ways to alleviate the possible problem of a high merger rate for the survival of disk galaxies. Hopkins et al. (2008) showed that angular momentum loss of the gas component is not necessarily catastrophic even in 1:1 mergers. Disks can survive or rapidly regrow, provided that the gas fraction in the disks of the progenitors is high (Robertson et al. 2006; Robertson & Bullock 2008; Bullock et al. 2008). If feedback is able to suppress star formation during the merger event (Brook et al. 2004; Robertson et al. 2006; Zavala et al. 2008; Governato et al. 2007) the existing cold gas can settle on a new disk plane and start regrowing a stellar disk.

Hydrodynamical simulations indeed show that cold flows (cold gas that flows rapidly to the center of galaxies from filamentary structures around halos (Kereš et al. 2005; Dekel & et al. 2008)) play a major role in the build up of disks in galaxies (Brooks & et. al 2008). Gas accreted through cold flows arrives to the central disk on a time scale a few Gyrs shorter than gas that is first shocked to the virial temperature of the host halo and then cools onto the disk, leading not only to early disk star formation, but the creation of a large reservoir of cold gas. No matter its origin, late infalling gas would likely have a higher angular momentum content than material accreted at earlier times (Quinn & Binney 1992) and gas in the merging disks would acquire a coherent spin set by the orbital parameters of the binary system and the internal spins of the parent galaxies. A feedback+cold flows model is particularly attractive as the mechanism for the survival/regrowth of disks as it provides a natural explanation to the fact that more massive galaxies tend to have large B/D ratios (Benson et al. 2007; Graham & Worley 2008), while smaller galaxies are likely disk dominated. At large galaxy masses energy feedback from supernovae (SNe) becomes ineffective at suppressing star formation while cold flows become inefficient at carrying a supply of fresh gas necessary to regrow a stellar disk (Dekel & Birnboim 2006). Combined with the relative higher frequency of major mergers for massive galaxies (Guo & White 2008) this framework leads to the

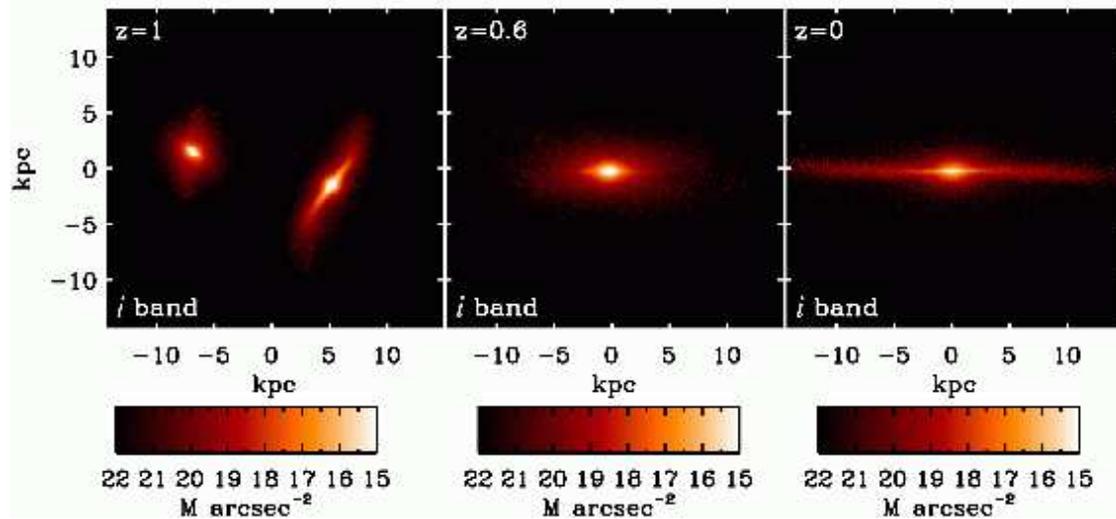
build up of a larger stellar spheroid and disfavors the quick rebuilding of stellar disks in massive systems.

Only recently have numerical simulations been able to directly compare the observable quantities of the outputs with real data (Jonsson 2006; Chakrabarti et al. 2007; Lotz et al. 2008; Covington et al. 2008; Rocha et al. 2008), rather than simply predicting the mass distribution of the simulated stellar systems. This is a crucial point as the stellar spheroids will fade drastically after a major merger, while reforming disks will contain a large fraction of younger and brighter stars. Different mass to light (M/L) ratios for the two components will skew the observed photometric light ratios compared to the underlying stellar masses.

Despite all of this progress, the effect of mergers on the existing disk components, and of feedback and cold flows on the regrowth of stellar disks have not been studied in detail in fully cosmological simulations of major mergers. Here we present results from a fully cosmological, smooth particle hydrodynamic (SPH) simulation where late gas accretion plays a major role in the rapid regrowth of a dominant stellar disk in an  $L^*$  galaxy after a  $z=0.8$  major merger. In this work we focus on the physical processes that drive the regrowth of the disk as identified by its kinematical properties, but we also measure the structural properties of the simulated galaxy based on the light distribution, i.e. in a way closely comparable to observations. This result helps solve the apparent contradiction that strong interactions at relatively low redshifts are common even for DM halos that are likely to host bright disk galaxies. The paper is organized as follows: §2 discusses the simulations, §3 describes the evolution of the system, §4 describes the observational properties of the merger remnant and §5 the assembly of the disk component. The results are then discussed in §6.

## 2 DESCRIPTION OF THE SIMULATION

The simulation described in this paper is part of a campaign of high resolution simulations aimed at studying the formation of field galaxies in a WMAP3 cosmology ( $\Omega_0=0.24$ ,  $\Lambda=0.76$ ,  $h=0.73$ ,  $\sigma_8=0.77$ ). Our sample of halos has been selected over two magnitudes in total mass (from  $2 \times 10^{10}$  to  $2 \times 10^{12} M_\odot$ ) sampling a representative range in halo spins and epochs of last major merger. The galaxy described in this paper has a total mass of  $7 \times 10^{11} M_\odot$ , spin  $\lambda = 0.04$  (as defined in Bullock et al. (2001)) and a last major merger at  $z=0.8$ . The environment density at  $z=0$  is typical of field halos with an over density  $\delta\rho/\rho = 0.1$  (0.2) measured over a sphere of radius 3 (8)  $h^{-1}$  Mpc. The final galaxy has 650k, 320k and 1.8m DM, gas and star particles within the virial radius of the galaxy at the present time, with particle masses:  $1.01 \times 10^6$ ,  $2.13 \times 10^5$  and  $6.4 \times 10^4 M_\odot$  for each DM, gas and star particle at the moment of formation. The force spline softening is 0.3 kpc. The minimum smoothing length for gas particles is 0.1 times the force softening. The simulations were performed with the N-body SPH code GASOLINE (Wadsley et al. 2004) with a force accuracy criterion of  $\theta = 0.725$ , a time step accuracy of  $\eta=0.195$  and a Courant condition of  $\eta_C=0.4$ . The adopted star formation and SN schemes have been described in detail in Stinson et al. (2006) and Governato et al. (2007). Our ‘‘blastwave’’ feedback scheme is implemented by releasing energy from SN into gas surrounding young star particles. The affected gas has its cooling shut off for a time scale associated with the Sedov solution of the blastwave equation, which is set by the local density and temperature of the gas and the amount of energy involved. At the resolution of this study this translates into regions of  $\sim 0.2-0.4$  kpc in radius being heated by



**Figure 1.** SDSS rest frame, unreddened *i*-band surface brightness images of the merging system at three different stages. Left (panel a):  $z=1.0$  close to the first pericentric passage. Center (panel b): the merger remnant at  $z=0.6$ , 1Gyr after the stellar cores of the two galaxies have coalesced. Right (panel c): the system observed at the present day: the halo has faded considerably while the galaxy has grown an extended thin disk. The *i*-band disk scale length  $R_d$  is 7.2 kpc and the light ratio of the kinematically identified Bulge and Disk components (B/D) is 0.49, while a GALFIT 2D decomposition gives a B/D = 0.65.

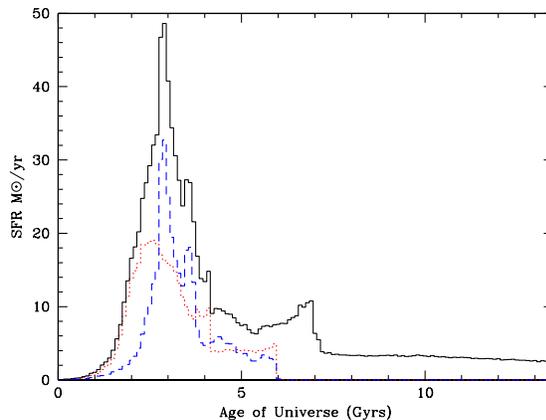
SN feedback and having their cooling shut off for 10-30 million years. The effect is to regulate star formation in the disks of massive galaxies and to lower the star formation efficiency in galaxies with circular velocity in the  $50 < V_c < 150$  km/sec range (Brooks et al. 2007). At even smaller halo masses ( $V_c < 20$ -40 km/sec, with  $V_c = \sqrt{M/r}$ ) the collapse of baryons is partially suppressed by the cosmic UV field (Hoefl et al. 2006; Governato et al. 2007), here modeled following Haardt & Madau (1996). The simulation applied a correction to the UV flux for self shielding of dense gas as introduced in Pontzen et al. (2008). It is important to note that the only two free parameters in the SN feedback scheme (the star formation efficiency and the fraction of SN energy coupled to the ISM) have been fixed to reproduce the properties of present day galaxies over a range of masses (Governato et al. 2007). Without further adjustments this scheme has been proven to reproduce the relation between metallicity and stellar mass (Brooks et al. 2007; Maiolino & et al. 2008) and the abundance of Damped Lyman  $\alpha$  (DLA) systems at  $z=3$  (Pontzen et al. 2008). However, even at this resolution the central regions ( $r < 1$ -2 kpc) of galaxies remain still partially unresolved and likely form bulges that are too concentrated (Governato et al. 2008; Mayer et al. 2008). In this respect the mass of the bulge component of our simulated galaxy has to be considered an upper limit imposed by current resolution limits, especially at high  $z$ , where the number of resolution elements per galaxy is less.

To properly compare the outputs from the simulation to real galaxies and make accurate estimates of the *observable* properties of galaxies, we used the Monte Carlo radiation transfer code *SUNRISE* (Jonsson 2006) to generate artificial optical images (see Figure 1) and spectral energy distributions (SEDs) of the outputs of our run. *SUNRISE* allows us to measure the dust reprocessed SED of every resolution element of our simulated galaxies, from the far UV to the far IR, with a fully 3D treatment of radiative transfer. Filters mimicking those of the SDSS survey (Adelman-McCarthy & et al. 2006) are used to create mock observations.

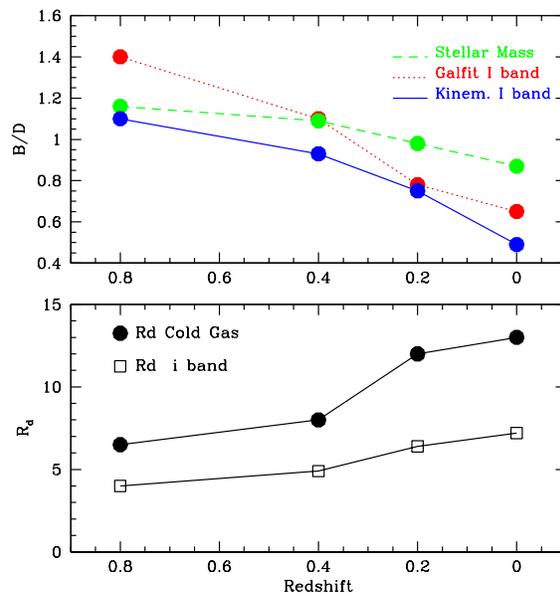
To measure the rotational velocity of the remnant and other galaxies in the sample in a way comparable with observations we used the spatial and kinematic distribution of cold gas in the disk of our simulated galaxy. Using the HI fraction calculated by GASOLINE, we determined the HI line width, ( $W_{20}$ ), by finding the width of the HI velocity distribution at 20% of the peak. The value of  $W_{20}/2$  is then used as a measure of the galaxy rotation velocity at different redshifts. This measurement reflects the mass weighted position-velocity distribution of cold gas inside the central region of the galaxy and in observed bright galaxies it is usually associated with the peak rotational velocity. Because the mass inside the central few kpc is likely overestimated owing to resolution effects (Mayer et al. 2008),  $W_{20}/2$  provides a slightly larger measurement of the rotational velocity than that obtained from the rotational speed of young stars at 2.2 or 3.5 disk scale lengths (typically 10–20kpc for bright galaxies), and thus is a useful upper limit for a comparison with real data.

### 3 DYNAMICAL AND PHOTOMETRIC EVOLUTION OF THE MERGING SYSTEM

The galaxy studied here was singled out for its particularly interesting assembly history, as the build up of its stellar component involves numerous major mergers, seemingly a hostile environment to build a significant stellar disk. At  $z=3$  the four most massive progenitors form a hierarchy of two binary systems roughly aligned



**Figure 2.** SFR vs time for the last major merger progenitors (red dotted and blue dashed) and for the whole galaxy (solid). The peaks of the dotted and dashed curves correspond to the two major mergers between the original four progenitors.



**Figure 3.** Lower Panel: Time evolution of the cold disk gas ( $T < 4 \times 10^4$  K) scale length and the stellar disk scale length (measured in the unreddened  $i$  band) of the final merger remnant. Upper Panel: The B/D ratio for the final remnant as a function of redshift: dashed: stellar masses. Dotted: B/D light ratio (unreddened  $i$  band) with a GALFIT decomposition based on the 2D, face on light profile. Continuous: B/D light ratio (unreddened  $i$  band) of the kinematically defined disk and bulge components.

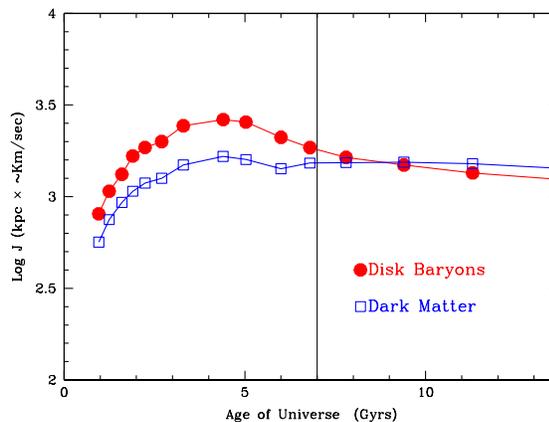
**Table 1.** Merger remnant properties at  $z=0.8$  (shortly after the merger) and at the present time.  $R_d$  is the disk scale length and B/D is the bulge to disk light ratio measured for the kinematically identified components. (B/D ratios in parentheses are measured using a 2D photometric decomposition with GALFIT of the face on projection of the light distribution). Total magnitudes and colors have been measured in SDSS filters, including the effects of dust (disk inclination 45deg) and in the AB system.

	$z=0.$	$z=0.8$
Tot Mag $i$ band	-22.3	-22.7
$R_d$ $i$ band (kpc)	7.2	4
B/D $i$ band	0.49 (0.65)	1.1 (1.4)
B/D (stellar mass)	0.87	1.16
$g - r$	0.5	0.4
SFR	$2.2 M_\odot/\text{yr}$	$6 M_\odot/\text{yr}$
disk stellar mass	$3.24 \times 10^{10}$	$2.07 \times 10^{10}$

on the same large scale filamentary structure. Each halo has a total mass  $\sim 7 \times 10^{10} M_\odot$  and has formed a rotationally supported stellar disk fed by strong cold flows, typical of galaxies at that redshift (Brooks & et. al 2008). In this work we define as ‘‘cold flow’’ gas that has never been shocked to  $3/8$  the virial temperature of the parent halo (Kereš et al. 2005; Brooks & et. al 2008). The average cold ( $T < 4 \times 10^4$  K) gas fraction of the four disks is 25% (defined as the fraction of baryons in the disk). Both pairs merge around  $z=2$ . Just before the mergers, the four progenitors have rest frame  $B$  magnitudes in the range  $-21.1 - -20.2$  ( $-21.5 - -20.6$  in the  $r$  band) and rest frame  $g - r$  colors around  $0.3 - 0.4$  (unless specified all global magnitudes and colors in this work are in the rest frame AB system and include the effects of dust reddening measured at a 45 deg inclination). These two early mergers are then ‘‘wet’’ i.e. between galaxies with blue colors as defined in Lin & et al. (2008).

Both merger remnants quickly reform extended disks from a combination of freshly accreted gas and gas already in the progenitors disks that was not turned into stars during the merger. For each merger the star formation history (SFH) peaked at 18 and  $32 M_\odot/\text{yr}$  respectively (Figure 2). At  $z=1.6$  (2 Gyrs before the final merger) the two disk galaxies formed from the early mergers have again very similar magnitudes:  $-21.6$  ( $-22.1$ ) and  $-21.3$  ( $-21.8$ ) in the  $B$  ( $r$ ) band respectively, close to the  $B$  band  $L^*$  at that  $z$  (Marchesini et al. 2007). Their  $g - r$  color = 0.4, makes them bluer than most galaxies of similar brightness at the present time (Lin & et al. 2008).

The final major merger of these two progenitor galaxies begins at around  $z=1$  when their dark matter halos, flowing along the same filamentary structure, first overlap. The galaxies plunge in on fairly radial orbits, with the internal spins of the two disks roughly aligned with the orbital angular momentum vector (Figure 1a). Note that this is not necessarily a configuration favorable to the survival of gaseous disks, as noted by Hopkins et al. (2008). After two close passages, the two galaxies coalesce by  $\sim z=0.8$ , i.e., 1 Gyr after the merger commenced. The mass ratio of the merging halos is 1.2:1 while the  $i$  band brightness ratio is 1.6:1. During the merger, the global star formation rate of the system is enhanced and peaks at  $11 M_\odot$  with subsequent star formation rates in the remnant dropping rapidly by almost factor of three to  $\sim 4 M_\odot/\text{yr}$  (Figure 2). The moderate star formation (SF) enhancement is consistent with estimates for interacting systems in the same redshift range (Jogee & et al. 2008). Given the galaxies’ properties outlined above, even this final merger is then clearly identified as ‘‘wet’’. However, the disks of the two galaxies have gas fractions around 20%, so they are only relatively gas-rich com-



**Figure 4.** The time evolution of the angular momentum content per unit mass of the kinematically identified  $z=0$  baryonic disk (gas and stars) and the dark matter of the merger remnant. The reference frame is defined by the center of mass of the selected particles. Disk material conserved most of the angular momentum gained by  $z=1.5$ . The vertical line marks the epoch when the halos and the baryonic cores merge during the last major merger.

pared to the present day population of galaxies of similar brightness (Garcia-Appadoo et al. 2008) and have equal or lower gas abundance as  $z \sim 2$  galaxies (Erb et al. 2006).

Once again, following the final major merger a disk rapidly regrows and star formation is mainly concentrated in the reforming disk. The galaxy remains relatively unperturbed after  $z=0.8$ . Shortly after the merger the spheroidal component of the newly formed galaxy dominates the light distribution (Figure 1b), although a disk component is already visible. The  $g - r$  color is 0.5 and remains stable to the present time. We verified that the disk component at  $z=0.8$  is indeed associated with a thick stellar disk supported by rotation. By  $z=0$  the galaxy has regrown an extended thin disk, while the spheroid has faded considerably. It has faded in the reddened  $B$  band by 0.8 mag to  $B = -21$ , due to the aging of the spheroidal component. The disk clearly dominates the light distribution in the SDSS  $i$  and bluer bands (Figure 1c).

These results show that at all stages the progenitors of the final galaxy can be identified with a normal population of moderately gas rich disk galaxies with colors and SF rates comparable with the galaxy population observed in the  $3 > z > 1$  range. It is also important to emphasize that the cold gas fraction in all the disk progenitors suggests that idealized initial conditions with disk gas fraction as high as 50% are not a necessary condition to have ‘‘wet’’ mergers and rapid regrowth of stellar disks. As discussed in §5 the fundamental ingredient for disk regrowth and blue colors is the fast refueling of gas from the hot halos and the surrounding cosmic web, highlighting the necessity of a fully cosmological approach to the problem of the abundance of galaxy disks<sup>1</sup>.

<sup>1</sup> Movie at [www.astro.washington.edu/fabio/movies/Merger.mpg](http://www.astro.washington.edu/fabio/movies/Merger.mpg)

#### 4 PROPERTIES OF THE MERGER REMNANT FROM $Z=0.8$ TO THE PRESENT

In this section we decompose our simulated galaxy into its kinematic components and “observe” some of its properties at the present day (they are summarized and compared with those of the galaxy at  $z=0.8$  in Table 1). Does the galaxy have the photometric and kinematic properties of disk dominated galaxies?

At the present time the disk clearly dominates the light distribution even in the relatively red  $i$  band (Figure 1c) The galaxy has a total magnitude is  $i = -22.3$  ( $-22.4$  unreddened) mag and global reddened color  $g - r = 0.5$ , consistent with those of luminous present day disk galaxies (Lin & et al. 2008).

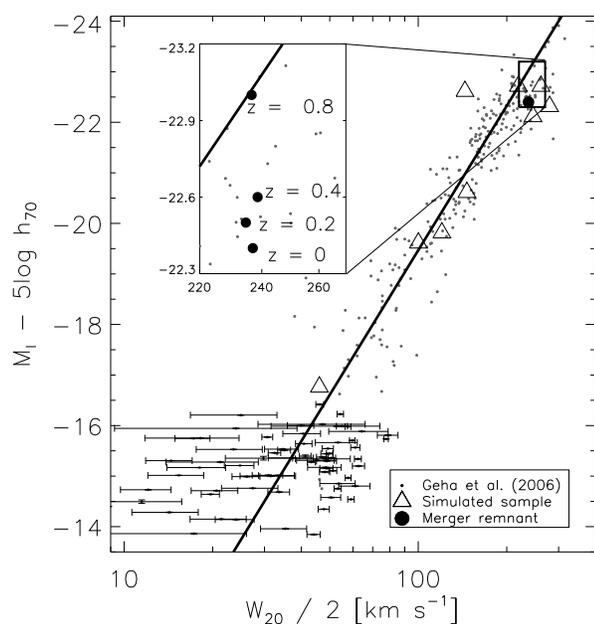
To measure its morphology in a quantitative way the different components of the galaxy were first identified using their kinematic and spatial information and classified as bulge, halo and disk. This is a crucial step to relate each galaxy component to its physical origin. Disk stars are defined as stars whose specific angular momentum perpendicular to the disk plane ( $j_z$ ) is a significant fraction of the maximum angular momentum of a circular orbit with the same binding energy ( $j_c$ ), i.e.  $j_z/j_c > 0.8$ . Particles on circular but highly inclined orbits are excluded. Bulge and halo stars were then identified based on their radial orbits and their binding energy (bulge stars being more bound). The energy separation criteria between halo and bulge stars corresponds to the radius at which the spheroid mass profile changes slope (halo stars having a shallower profile than bulge stars) and in our simulated galaxy sample separates an older and metal poor population (the halo) from bulge stars that are more metal rich. Halo stars contribute a fraction ( $\sim 15\%$ ) of the total stellar mass within the virial radius of the galaxy, but the halo central density is two orders of magnitude lower than that of the bulge. Hence the details of the bulge/halo decomposition do not change our conclusions. At  $z=0$  the kinematically identified disk, bulge and halo stellar masses are respectively: 3.4, 2.7 and  $1. \times 10^{10} M_\odot$ . We then imaged each separate component using *SUNRISE* and measured their structural parameters using the unreddened images. We focused on a structural analysis of the unreddened components, avoiding the additional layer of complexity given by the details of the dust distribution, which will be explored in future papers with a larger number of galaxies. However, we have verified that our findings do not change if the reddened images are used instead.

How and when did the disk reform after the last major merger at  $z=0.8$ ? The stellar disk and bulge components were identified at different redshifts after the last major merger event. To better understand the B/D ratio evolution of the merger remnant we measured B/D in three different ways. We used the kinematic decomposition to find a) the stellar mass ratio of the bulge and disk components and b) their relative flux ratio in the  $i$  unreddened band. Then we analyzed the unreddened, face-on 2D light distribution created by *SUNRISE* using all the galaxy star particles (including halo particles) with GALFIT (Peng et al. 2002) to find c) the B/D ratio as determined by a fit to the surface brightness profile. Figure 3 shows how the  $i$  band disk scale length and the B/D ratio evolve with time. Shortly after the merger event the disk component is already visible edge-on, then the bulge component fades relative to the disk and the disk becomes more extended. At  $z < 0.4$ , or about 3.5 Gyrs after the merger, the disk dominates both in terms of the light contribution and the B/D ratio decreases further by  $z=0$ . All measurements agree on the same trend of B/D decreasing with time. At the present time the disk extends almost far as 20 kpc in radius from the galaxy center and the stellar disk scale length  $R_d$  is 7.8 and 7.2 kpc in the

B and  $i$  bands, respectively (Figure 3), consistent with observations of real galaxies that show larger  $R_d$  in bluer bands. Smaller B/D ratios are obtained using the light distribution, more sensitive to the younger ages of disk stars. At  $z=0$  the B/D stellar mass ratio of the kinematically defined components is 0.87, but the unreddened  $i$  band light ratio is only 0.49. GALFIT shows the steepest trend with age, and shortly after the merger it underestimates the disk component, if by less than 20%. GALFIT gives a fairly precise estimate of the light weighted B/D ratio when the stellar disk becomes dominant.

Soon after the merger the cold gas disk increases its size by nearly a factor of two as the new infalling gas settles on high angular momentum orbits. The angular momentum of the present day disk baryons is mostly acquired at high  $z$  (Figure 4) as predicted in analytical models (Quinn & Binney 1992) with a fraction of it transferred to the DM halo during the last major merger. As this gas is gradually converted into stars the stellar disk also grows in size, however the cold gas disk remains significantly more extended than the stellar one. Shortly after the merger the (unreddened  $i$  band) disk scale length is 4 kpc, at the present time it is almost twice as large, with only minor warping (Figure 7). Most likely due to the late assembly of its younger component, this is a fairly extended disk for galaxies of this mass, more extended than many disks formed in cosmological simulations where the assembly history of the galaxy was more “quiet”. Encouragingly, we verified that the structural properties of the bulge and disk do not change much if they are measured using GALFIT on the global unreddened 2D light distribution, i.e. without a prior knowledge of the kinematic decomposition. With GALFIT the  $i$  band  $R_d$  is 6.8 kpc, a 5% difference. GALFIT finds systematically larger B/D ratios, but only by 20% or less. However, B/D ratios decrease if the GALFIT fitting is done on dust reddened images. These B/D ratio and  $R_d$  are quite typical of bright Sa and Sb galaxies that typically have dust corrected B/D  $\sim 0.5$  and red  $R_d \sim 3-7$  kpc (Graham & Worley 2008; Driver et al. 2007; Benson et al. 2007).

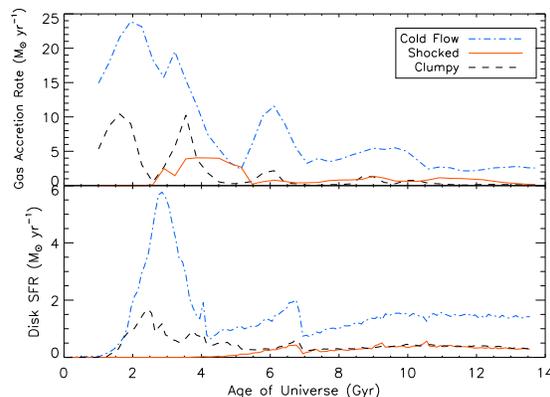
To show how the simulated galaxy of this study relates to the general population of real disk galaxies on the Tully Fisher (TF) relation, we compared its HI velocity width  $W_{20/2}$  (238 km/sec) and total rest-frame unreddened  $i$ -band relation with some of the other galaxies in our sample of simulated galaxies with the sample of disk galaxies described in Geha et al. (2006) and references therein (Figure 5). We find that the agreement between the observed TF and our set of simulations is quite good, as the combination of high resolution and the feedback adopted in our simulations yields a good match to real galaxies over a wide range of magnitudes and circular velocities. The merger remnant object of this study lies well within the observed scatter of both the observed and simulated samples, confirming that its structural properties are similar to those of typical bright spiral galaxies. We will present the scaling properties of the full data-set of simulated galaxies in a forthcoming paper. An interesting feature of the Tully Fisher plot is the evolution of the remnant on the TF plane: the very limited growth of the bulge stellar mass (only a few %) and the inside out growth of the disk ensures that the amount of mass within the central region of the galaxy does not change, hence  $W_{20/2}$  does not evolve strongly, while the overall fading of the stellar components makes the galaxy dimmer by less than half a magnitude between redshift 0.8 and 0 (see Table 1). Even if the assembly history of our galaxy is not typical of galaxies of similar total mass, this result is consistent with observations that find a small evolution in the observed galaxy TF relation up to  $z=1$  (Conselice et al. 2005) along with strong size evolution



**Figure 5.** The location of the simulated galaxy in this work on the present day “Tully-Fisher” relation, i.e., the unreddened  $i$  band vs  $W_{20}/2$ . Grey dots: Galaxies from a compilation of observational data (Geha et al. 2006). Triangles: other disk galaxies from our simulated sample at similar resolution. Filled dot in main panel: the galaxy of this study at  $z=0$ . Filled dots in upper left insert: different snapshots of the merger remnant from  $z=0.8$  to the present. Circular velocities are the  $W_{20}/2$  velocity widths from the HI distribution of the simulated galaxies. The insert shows the weak redshift evolution of the merger remnant on the TF plot.

(Trujillo et al. 2007). This result is not trivial and we plan to extend this analysis to our full sample of simulations in a future work.

We also verified that the metallicity of the cold gas is consistent with the observed stellar mass - metallicity relation ( $8.5 < 12 + \log(\text{O}/\text{H}) < 8.9$ , depending on the aperture used, Tremonti & et al. 2004; Brooks et al. 2007). An average metallicity consistent with real galaxies is an important test of the realism of this simulation and makes the estimates of the galaxy colors of the final remnant and its progenitors more robust. Finally, the satellite system of the remnant includes 11 resolved luminous satellites within the virial radius of 230 kpc. The faintest has AB B mag = -8.7, the brightest -17.9. By tracking the satellites through different outputs after the merger event we verified that the galaxy disk undergoes several fly-bys by small dark satellites, but no significant accretion of luminous satellites after the final merger. Many faint satellites have undergone severe tidal stripping of both their DM halos and of their stellar component. This analysis quantifies the dramatic regrowth of the disk component and how, coupled with the fading of the bulge and halo components it leads to the formation of a galaxy dominated by an extended disk. It also highlights the difference between evaluating a galaxy morphological type using the mass distribution compared to the light distribution. It is encouraging however, that similar trends (growing disk size and decreasing B/D ratios) are recovered using complementary techniques, as GALFIT provides a decomposition into bulge and disk components quite similar to that obtained using the full spatial and kinematic information. These results support the notion that the ob-



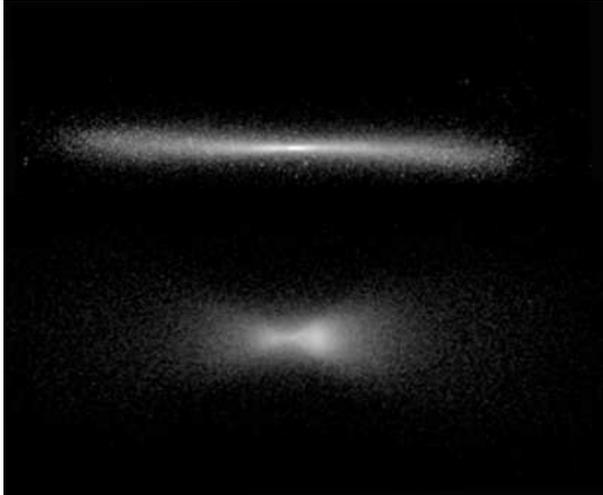
**Figure 6.** Top Panel: The total gas accretion history of the merger remnant, divided by the thermodynamical history of the gas. (at high  $z$  the lines are the sum of the contributions from individual progenitors). Bottom Panel: The SFH of disk star particles separated by the history of their parent gas particles. The disk stars are kinematically identified at  $z=0$ . Dashed: from clumpy gas accretion, dot dashed: from unshocked gas (or “cold flows”), solid: shocked gas. A significant fraction of stars formed at high  $z$  and were identified as part of the disk even after two major mergers. At the present time they form the thick disk component (see also Figure 7). Star formation in the disk is partially disrupted during the last major merger, and stars formed from gas cooled from the hot halo form a significant fraction of the younger disk component.

served B/D ratios in bright galaxies are indeed representative of the underlying dynamical disk and spheroidal components.

## 5 THE ASSEMBLY OF THE GALAXY DISK

A detailed analysis of the gas accretion history was performed by tracking backward every gas particle that was ever within the virial radius of the simulated galaxy and its progenitors. Every star particle comes from a gas progenitor which is uniquely identified at the moment of the star particle formation. The thermodynamical history of each gas particle progenitor was then studied. This temperature history was done for each of the original four progenitor galaxies, then again for the resulting two binary galaxies, and finally for the merger remnant. Gas particles were then classified as a) “cold flows” if it never belonged to a progenitor halo before being accreted onto one of the progenitor galaxies or the merger remnant and it never shocked to  $> 3/8$  the virial temperature of the galaxy, b) “shocked” if the gas was first shocked to  $> 3/8$  the virial temperature of the main halo and then cooled onto the disk, and c) “clumpy” if the gas particle was assigned to a subhalo before becoming part of the disk (i.e., a halo other than one of the four main progenitors and their subsequent merger remnants).

Figure 6 shows (top panel) the total gas accretion rates to progenitor galaxies and merger remnant, and (bottom panel) the SFH of the resulting disk (as identified at  $z=0$  based on the stellar kinematics), separated by the different histories of each gas particle progenitor. It is remarkable that a large fraction of the disk formed at redshift one or earlier, when the galaxy had not undergone its last major merger yet. This result supports the suggestion that major mergers do not always completely destroy the pre-existing disks (Hopkins et al. 2008), although they heat them quite substantially, making them thicker. Cold flows build the largest fraction of the disk up to low redshift. This analysis shows how the build up of the



**Figure 7.** The  $i$  band (unreddened) edge on image of the galaxy disk at  $z=0$ . Upper Panel: light distribution from stars formed after the last major merger. Lower panel: the light distribution from stars formed before the last major merger, but still identified as disk based on their angular momentum. The image is 40 kpc across. The relative brightness of the two components is not to scale.

disk of bright galaxies differs from the simple picture of gas cooling from the hot halo and assembling into a disk; only at later times does gas cooling from the hot halo phase plays a role. From Figure 6 it is clear that cold flows dominate the early gas accretion history of the progenitor galaxies, and is the dominant source of SF in the galaxy disk. Because SN feedback regulates SF in the disk, a cold gas reservoir is able to develop that sustains SF until the present time. The SF rate drops significantly when the two progenitor disk galaxies merge at  $z\sim 1$ . After this time, gas cooling from the hot halo becomes more important, resulting in 30% of the disk stars formed in the last 2 Gyrs formed from gas labeled as shocked. However, only 10% of the total amount of stars in the disk at the present time have formed from gas that was previously heated to the virial temperature of the main progenitor. We find that this result is quite typical for disk galaxies of total mass  $< 10^{12} M_{\odot}$  (Brooks & et. al 2008) stressing the role of cold flows in building early disks and of “shocked” gas in rebuilding the young, and hence bluer, more metal rich and brighter part of the disk. These effects will have to be carefully modeled in semi analytical models of galaxy formation. Figure 1 shows that as the disk grows in mass, most of the stars are added to a thin and dynamically cold part of it. To quantitatively evaluate this process we separated the stars previously dynamically identified as disk into two populations: those that formed before the  $z=0.8$  merger and those formed after, i.e in the last  $\sim 6$  Gyrs. Figure 7 shows the edge-on  $i$  band surface brightness image (unreddened) of the two populations. Their properties are strikingly different: the younger stars form a thin exponential disk with  $i$  band scale length of 8.4 kpc (measured using stars in the 2-13 kpc range) and scale height of just 0.5 kpc (measured as a Gaussian distribution at a radius of 8.5 kpc). This scale height is likely as small as allowed by the force softening of 0.3 kpc. The older component, while being comparable in mass, is 1.3 mag fainter in the  $i$  band and 2.2 mag in the B band. It also has a much shorter disk scale length, 3.1 kpc, and is considerably thicker, 2.7 kpc, again at an 8.5 kpc radius. The flaring in the old disk is due to the kinematic selection criteria, that exclude particles on circular orbits that are highly inclined from the disk plane.

While beyond the scope of this paper, we speculate that the mix of the two components could easily be identified as a thick and thin disk components if observed using typical observational techniques (Yoachim & Dalcanton 2006). Results from this simulation support the notion that thick disks are formed during major mergers and the early assembly of galaxy disks (Brook et al. 2004). Furthermore, the last major merger should leave a clear signature in the age distribution of thick disk (which will be older than the merger) and thin disk stars (mostly formed after the merger).

In this realization no significant component of the stellar disk formed by accretion of stars in smaller satellites through minor mergers. While a substantial galaxy to galaxy scatter is expected, this is consistent with results from our larger sample of simulated disk galaxies (Brooks & et. al 2008) and, compared with the existing literature, a consequence of the smaller stellar masses of the galaxy satellites resulting from the realistic feedback implementation (Governato et al. 2007). We verified that the bulge grows only modestly in mass from  $z=0.8$  to  $z=0$  and that no strong bar instabilities form after the last major merger. Similarly the halo component shows minimal mass growth during the same time period. A close examination of the time evolution of the system shows several passages and disruption of small dark satellites, but they do not prevent the system from reforming a thin stellar disk.

## 6 CONCLUSIONS

We have analyzed an SPH, fully cosmological simulation of the evolution of a galaxy that grows an extended thin stellar disk after a major (1.6:1) merger at  $z=0.8$ . The disk dominates the light distribution 3.5 Gyrs after the merger. By the present time the galaxy shares several properties with the observed population of disk dominated  $L^*$  galaxies.

This result is particularly relevant as the assembly history of the galaxy’s parent DM halo is different from many previously published studies of cosmological simulations of disk galaxies, as it undergoes a late major merger, whereas previous works tended to select galaxies with a relatively quiet merger history. The two progenitors underwent major mergers themselves, at  $z\sim 2$ . The end result of this simulation strongly contradicts the notion that disk formation requires a “quiet” halo merging history. In fact, the merging history of the halo picked for this study has often been considered hostile to the formation of extended disks at the present time. Our study provides strong support to the notion that galaxy disks can reform in a few Gyrs after a gas rich major merger, while a fraction of the pre-existing stellar disk can survive, even if faded by age and thickened by the strong interaction.

The results of our analysis are made particularly robust by measuring the properties of the remnant light distribution rather than just that of the stellar mass. This approach is crucial, as it highlights the effects of fading of the light from older stellar populations and plays a major role in quantifying the predominance of the newly formed (and hence bluer and brighter) stellar disk. The main structural parameters of the galaxy at  $z=0$  suggest that it has an Sa or Sb morphology: reddened  $i$  band  $B/D\sim 0.65$ ,  $R_d = 7.2$  kpc,  $g-r = 0.5$ , a  $W_{20}/2$  HI velocity width of 238 km/sec. Moreover, being able to measure the reddened colors and brightness evolution of the progenitors allows us a comparison with high- $z$  galaxies, showing that they are representative of the population of blue, gas rich and moderately star forming galaxies observed at  $z>1$ . Verifying that the progenitors have some of the observed properties of high redshift galaxies is important, as it makes the present day properties of

the merger remnant more relevant, having been built from realistic progenitors.

As our simulation includes a full treatment of the cosmological environment it includes a realistic treatment of a number of hydrodynamical processes that are necessary for the regrowth of stellar disks and that have to be simultaneously included: stellar feedback, continuous inflow of gas from the cosmic web and cooling from hot halo gas. This explains the difference between our results and those of the collisionless simulations of Purcell et al. (2008), which showed significant disk heating due to interactions and accretion events. Lack of gas infall prevented the disks in their simulations to regenerate a new thin component (gas resupply was in fact advocated as a possible solution). In our simulation the effect of interactions with infalling satellites, both luminous and dark, is naturally included. However, interactions and minor mergers are not strong enough to significantly disrupt or thicken the disk as it reforms from new gaseous material.

Idealized hydrodynamic simulations of binary galaxy mergers (Robertson et al. 2006; Hopkins et al. 2008) did not include the continued infall of gas from cold flows and the hot halo. These works pointed out that without any subsequent accretion/growth onto the disk after the merger, a cold gas fraction in excess of 50% would be required in the disks of the progenitors in order to re-build a disk dominated galaxy after the merger. Here we have shown that such high disk gas fractions are not necessary, as cold flows and cooling from a hot halo make disk regrowth possible even at low redshifts, when the gas fraction in the progenitors' disks and the remnant is only  $\sim 20\%$  at any given time. The analysis of the build up of the disk in our simulated galaxy highlights the dominant role of cold flows at high redshift. Cold flows funnel gas to the central disk on a time scale a few Gyrs shorter than gas that is first shocked to the virial temperature of the host halo and then cools onto the disk, leading not only to early disk star formation, but the creation of a large reservoir of cold gas. Thus, if a substantial fraction of this cold gas reservoir survives a merging event, it can provide a faster accretion rate onto the reforming disk than that available from cooling the hot gas in galaxy halos alone. Rapid disk reformation will also be aided if cold gas accretion onto the galaxy halo is still occurring, while gas cooling from the hot phase forms just 30% of the post merger stellar disk. However, this young component is more evident when the system is observed in bluer bands. It is important that these processes of disk formation and destruction be carefully implemented in analytical models that study the properties of large sample of galaxies.

More work is also needed to make detailed quantitative predictions about the morphology of galaxies formed in cosmological simulations and to make the results of our study more general. The maximum halo mass and lowest redshift at which mergers can regrow disks are obviously a function of the feedback efficiency (Brook et al. 2004; Scannapieco et al. 2008) and could therefore provide useful qualitative tests of models of SF and feedback. In dense environments, such as groups or clusters, the gas reservoir associated with cold flows and cooling halo gas will likely be disrupted by tidal forces and ram pressure stripping. Hence the disk re-growth process should be much less efficient, as expected by the observed correlation between galaxy morphology and environment density. Also, higher resolution cosmological simulations will have to address the role of secular processes on the detailed structure of the bulge and thin disk components and their role in setting the B/D ratio of galaxies (Debattista et al. 2004; Genzel & et al. 2008; Weinzirl et al. 2008). Still, results of the work presented here greatly alleviate the problem posed for the existence of disk galax-

ies by the high likelihood of interactions and mergers for galaxy sized halos at relatively low  $z$ .

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