A MERGER-DRIVEN SCENARIO FOR COSMOLOGICAL DISK GALAXY FORMATION

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ABSTRACT

The violent hierarchical nature of the Λ-Cold Dark Matter cosmology poses serious difficulties for the formation of disk galaxies. To help resolve these issues, we describe a new, merger-driven scenario for the cosmological formation of disk galaxies that supplements the standard model based on dissipational collapse. In our picture, large gaseous disks are produced from high-angular momentum mergers of gas-rich progenitors. Pressurization from the multiphase structure of the interstellar medium and thermal feedback from supermassive black holes prevents the complete conversion of gas into stars during the merger, and if enough gas remains to form a disk the remnant eventually resembles a disk galaxy. We perform numerical simulations of galaxy mergers to demonstrate that disks can build angular momentum through mergers and the degree of rotational support of the baryons in the merger remnant is directly related to feedback processes associated with star formation and black hole growth. The correlation between black hole mass and the stellar velocity dispersion is connected to the formation of galactic disks as feedback from black hole growth limits the mass of the bulge component and increases the available gas supply for forming rapidly rotating stellar disks. We suggest that the hierarchical nature of the Λ-Cold Dark Matter cosmology, the physics of the interstellar gas, and the growth of supermassive black holes can act together to form spiral galaxies by building the angular momentum of disks through gas-rich mergers. Our proposed scenario is especially important for galaxy formation at high redshifts, where gas-rich mergers are believed to be more common than in the local Universe.

Subject headings: galaxies: formation – galaxies: evolution

1. INTRODUCTION

The conventional theory for the origin of disk galaxies in Cold Dark Matter (CDM) cosmologies involves the dissipational collapse of gas inside relaxed dark matter halos formed through hierarchical clustering (White & Rees 1978; Blumenthal et al. 1984). This theory endows forming disk galaxies with kinematic properties inherited from the halos that host them (Fall & Efstathiou 1980). Early simulations of cosmological structure formation (Barnes & Efstathiou 1987) verified that during linear growth, the angular momentum of halos grows according to perturbation theory (Peebles 1969), and by incorporating these results subsequent work explained the flat rotation curves and sizes of disk galaxies through the combination of gas dissipation, halo spin, and the adiabatic response of dark matter to baryonic infall (Blumenthal et al. 1986; Mo et al. 1998). The initial success of the dissipational collapse model led to its establishment as the favored theory for the formation of disk galaxies. However, numerical modeling revealed that the theory was incomplete.

While smooth, dissipational collapse may be relevant to disk galaxy formation in quiet environments, dissipationless simulations have demonstrated that it is rare for dark matter halos to acquire most of their angular momentum via the quiescent accretion of tidally torqued material (Vitvitska et al. 2002; Maller & Dekel 2002). Furthermore, simulations of mass accretion onto galaxies indicate that the hierarchical nature of the ΛCDM cosmology leads to the destruction of disks when dissipative effects are neglected (Toth & Ostriker 1992; Quinn et al. 1993; Walker et al. 1996; Velazquez & White 1999). Models of galaxy collisions including dissipation (Hernquist 1989; Barnes & Hernquist 1991, 1996) show that gas can loose angular momentum owing to gravitational torques during these events. In cases when the interstellar medium (ISM) is isothermal and relatively cold and the gas fraction of the galaxies is small ($\sim$ 10% of the baryons), the subsequent inflow of gas into the centers of the merger remnants forms a roughly spherical stellar distribution through a luminous starburst (Mihos & Hernquist 1994, 1996), leaving objects that have essentially no stellar disks. Cosmological simulations of disk formation with similar physics produce galaxies that are too centrally concentrated, form too many stars, contain overly dominant bulges, and lack angular momentum compared with nearby spirals (Katz & Gunn 1991; Katz et al. 1992; Navarro & White 1994; Steinmetz & Muller 1995; Navarro & Steinmetz 2000).

Efforts to resolve these discrepancies in a cosmological context have mainly relied on increasing the impact of feedback from star formation (Weil et al. 1998; Sommer-Larsen et al. 1999, 2003; Thacker & Couchman 2000, 2001; Abadi et al. 2003; Governato et al. 2004; Robertson et al. 2004). Cosmological and isolated merger simulations that utilize strong feedback from star formation in the form of a pressurized ISM to produce disk galaxies either produce too few exponential disks compared with observations (Robertson et al. 2004) or yield galaxies that still contain a significant bulge component (Springel & Hernquist 2005). While these recent simulations have had some success, taken together the results suggest the origin of disks is un-

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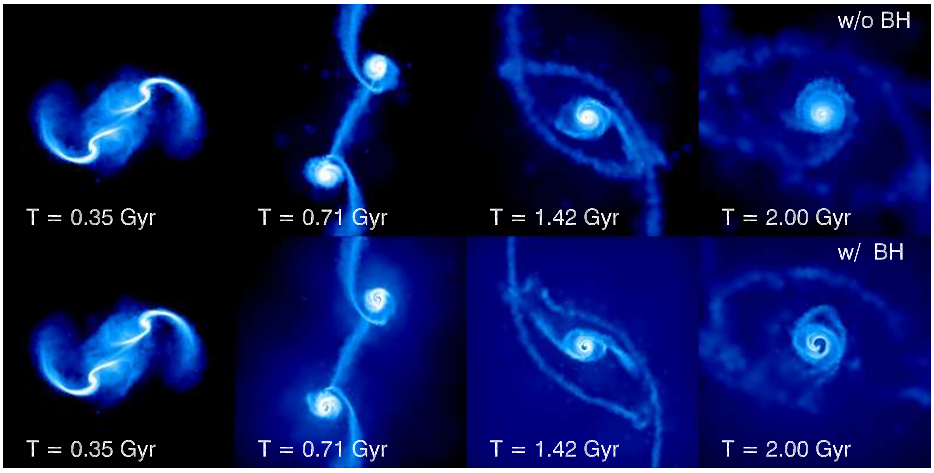

FIG. 1.— Merger of two gas-rich disk galaxies, with (bottom) and without (top) supermassive black hole accretion and feedback. Shown is the gas surface density of the galaxies in each 140×140 kpc square panel, demonstrating that the high-angular momentum merger results in a remnant disk. The effects of black hole feedback can be seen over the 2 Gyr time scale of the merger as a diffuse, hot halo and the lowered central gas density in the remnant (bottom panel).

likely to be explained by feedback from star formation alone and additional sources of energetic feedback could be important. The theory of structure formation remains faced with an apparent incompatibility between models of disk formation and the hierarchical growth of structure.

To resolve this incompatibility, we propose a new, merger-driven theory for the formation of disk galaxies that supplements standard dissipational collapse. In our scenario, black hole feedback provides an important and previously neglected source of energy during the merging process. When combined with the gas pressurization from a multiphase ISM by feedback from star formation (McKee & Ostriker 1977; Springel & Hernquist 2003), which stabilizes gas disks and allows mergers between gas-dominated galaxies to produce large, smoothly distributed stellar disks, thermal feedback from accretion onto supermassive black holes (BHs) regulates the growth of the spheroidal component of the remnant (Di Matteo et al. 2005). The energetic feedback from BH accretion then links the observed BH mass - stellar velocity dispersion ($M_{\rm BH}-\sigma$) relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) to the formation of disks as the impact of BH growth on the mass of the bulge component of galaxies increases the gas supply available to form a disk and, together with the stabilizing influence of pressurization of the multiphase ISM, yields a rapidly rotating stellar disk.

2. METHODOLOGY

To demonstrate the feasibility of our scenario for merger-driven disk formation, we have performed a suite of merger simulations of isolated, gas-rich disk galaxies, with and without feedback from accretion onto supermassive BHs. The simulations use Smoothed Particle Hydrodynamics (SPH) (Lucy 1977; Gingold & Monaghan 1977) to evolve the gas and incorporate a multiphase ISM model (Yepes et al. 1997; Hultman & Pharasyn 1999; Springel & Hernquist 2003; Springel et al. 2004) where we control the pressurization $q_{\rm EOS}$ of star-forming gas by interpolating between isothermal gas ($q_{\rm EOS} = 0$) with a temperature $T_{\rm eff} = 10^4$ K and a stiffer multiphase medium ($q_{\rm EOS} = 1$) with a higher effective temperature $T_{\rm eff} \approx 10^5$ K by varying the equation of state (EOS; for details see Springel et al. 2004). Star formation in the dense ISM ($\Sigma > 10 M_\odot$ pc^{-2}) occurs on a timescale chosen to match observations (Kennicutt 1998). BH growth is modeled (Springel et al. 2004) by spherical accretion onto BH "sink" particles, with a fraction $\epsilon_{\rm f}$ of the released gravitational potential energy of the accreted gas being deposited as thermal feedback into the gas surrounding the BH. For the simulations and accretion model considered here, $\epsilon_{\rm f} = \eta_{\rm therm}\epsilon_{\rm r} = 0.005$, where $\epsilon_{\rm r} \approx 0.1$ is the fraction of rest mass energy radiated during the growth of the BH (fixed by standard accretion theory) and the thermal coupling efficiency $\eta_{\rm therm} = 0.05$ is chosen to reproduce the local $M_{\rm BH}-\sigma$ relation (Di Matteo et al. 2005).

The merger progenitors consist of two identical galaxies (Springel & Hernquist 2005) having rotational velocities $V_{\rm vir} = 160$ km s^{-1} at their virial radii, with rotation curves and virial masses $M_{\rm vir} = 9.5 \times 10^{11} h^{-1} M_\odot$ similar to the Milky Way. The galaxies are comprised of a 99.9% exponential gas disk, $M_{\rm disk} = 3.9 \times 10^{10} h^{-1} M_\odot$, embedded in dark matter halos with a Hernquist profile (Hernquist 1990) having scale lengths corresponding to a Navarro-Frenk-White (Navarro et al. 1997) concentration of $c_{\rm NFW} = 9$. The progenitors each contain 40000 gas, 40000 stellar, and 60000 dark matter halo particles, and may also include a BH seed of $10^5 h^{-1} M_\odot$ located at the potential minimum of each galaxy and allowed to accrete in the manner described above. Once the BH particles fall within our force resolution limit, the sink particles combine into a single supermassive BH. The galaxies merge on coplanar, prograde orbits with an initial separation $R_{\rm init} = 70 h^{-1}$ kpc and pericentric distance $R_{\rm peri} = 6 h^{-1}$ kpc. The merger orientation considered here is intended to capture the gross behavior of high-angular momentum collisions only and to establish the feasibility of our proposed scenario for merger-driven disk formation. However, we note from additional simulations that the results described here are not peculiar to the orbit we adopt.

Figure 1 shows the time evolution of the gas in a merger with a moderately pressurized ($q_{\rm EOS} = 0.5$) ISM with (bottom panel) and without (top panel) feedback from accretion onto supermassive BHs. Each panel shows a 140 kpc $\times$ 140 kpc square area around the center of mass of the interacting system. At early times in the merger ($T = 0.35$ Gyr, far-left panels), tidal interactions between the galaxies distort them, but as significant accretion onto the BHs has yet to occur, the

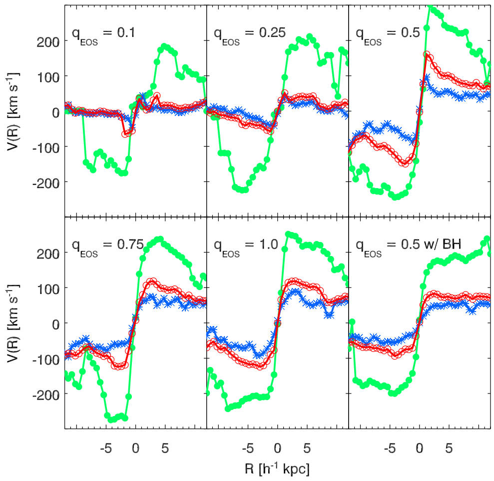

FIG. 2.— Stellar rotation curve of merger remnants, for models with differing ISM pressurization. Shown is the rotation of stars formed before the merger ($T < 0.3$ Gyr, blue), after the merger ($T > 1.2$ Gyr, green), and for all stars in the system (red). The amount of rotation in the disk remnant correlates strongly with gas pressurization, increasing from the upper left panel ($q_{\rm EOS} = 0.1$) to the bottom middle panel ($q_{\rm EOS} = 1.0$). The nearly isothermal ISM model ($q_{\rm EOS} = 0.1$) produces almost no net rotation in the stellar disk, while moderately to strongly pressurized models ($q_{\rm EOS} = 0.5-1.0$) produce a rotating stellar component. The lower right panel shows a moderately pressurized ISM model ($q_{\rm EOS} = 0.5$) with BHs, depicting the flattened rotation curve owing to the reduction of the bulge component by the effects of BH feedback.

overall gas distribution remains similar between the simulations. As the gas in the simulation with BHs (bottom panels) begins to experience thermal feedback from BH accretion, a hot halo of diffuse gas expelled through a wind surrounds the interacting galaxies. By the end of the simulations at $T = 2.0$ Gyr (far-right panels), rotating gas disks remain, eventually forming stellar disks. The remnant containing a BH has cleared out some gas from the inner regions of the disk, reducing the central stellar density and producing a diffuse hot gas envelope.

3. RESULTS

The kinematic properties of the remnants exhibit significant quantitative differences as the pressure support of the ISM is varied. The stellar rotation curves of the merger remnant in the $q_{\rm EOS} = 0.1, 0.25, 0.5, 0.75$, and 1.0 models without BHs are plotted in Fig 2. The strength of the rotating stellar component correlates with the pressurization of the ISM. The weakly pressurized ($q_{\rm EOS} = 0.1$), nearly isothermal model yields a remnant with almost no rotational support, in agreement with cosmological and galaxy merger simulations that galaxies formed from an isothermal gas resemble ellipticals. The moderately to strongly pressurized ($q_{\rm EOS} = 0.5-1.0$) models produce remnant stellar disks that are rapidly rotating. Also shown is the $q_{\rm EOS} = 0.5$ model with BHs (bottom right panel), where the feedback from BH accretion has decreased the bulge component and flattened the rotation curve. As these simulations demonstrate, disk galaxy remnants containing rapidly rotating stellar components can form from high-angular momentum, gas-rich mergers when the ISM is pressurized.

Typically, even remnants formed in high-angular momentum mergers will contain a significant bulge component. However, including feedback from accretion onto BHs in these simulations reveals an intriguing connection between the creation of stellar bulges, powerful BH feedback, and the formation of stellar disks. Figure 3 shows the stellar surface mass density of the remnant in a moderately pressurized ISM ($q_{\rm EOS} = 0.5$) case without (left panel) and with (right panel) accretion onto BHs. The final remnant lies within 2-3 standard deviations of the local $M_{\rm BH}-\sigma$ relation, with the mass of the central stellar bulge component left by the merger decreasing by a factor $\sim 6\times$ owing to the impact of BH feedback. For a given ISM pressurization, feedback from gas accretion onto supermassive BHs decreases the size of the bulge in the remnants and increases the mass of the rotating stellar component relative to the mass of the spheroid.

Not only does feedback from BH growth during a merger explain the correlation between BH mass and stellar velocity dispersion in the remnant (Di Matteo et al. 2005), our simulations show that it plays an important role in the formation of stellar disks because it regulates both the mass of the non-rotating component of the remnant and the amount of gas available to form future generations of orbiting stars once hot gas driven into the halo can cool and accrete onto a disk. For example, the final stellar mass of the remnant in the $q_{\rm EOS} = 0.5$ ISM run with BHs is $4.47 \times 10^{10} h^{-1} M_{\odot}$, as BH feedback and ISM pressurization limit the conversion of gas into stars and leaves a total gas mas of $3.32 \times 10^{10} h^{-1} M_{\odot}$. Once the hot halo gas cools this remnant will reach a mass-weighted stellar rotational velocity of $V_{\rm rot} \sim 175$ km s^{-1} as the rotating gas disk forms stars and evolves to within a factor of ~ 2 in $V_{\rm rot}$ of the local Tully-Fisher (Tully & Fisher 1977) relation for spiral galaxies. By contrast, the nearly isothermal ISM model ($q_{\rm EOS} = 0.1$) without BH feedback has a final stellar mass of $7.35 \times 10^{10} h^{-1} M_{\odot}$ and a small residual gas mass of $4.59 \times 10^{9} h^{-1} M_{\odot}$. Without a large resevoir of gas in the remnant to form a stellar disk, this slowly rotating galaxy will never reach the Tully-Fisher relation. We therefore emphasize that BH feedback effectively controls the bulk properties of the disk galaxy merger remnant and should not be ignored in theories of disk galaxy formation.

4. DISCUSSION

As this work demonstrates, the impact of BH feedback on galaxy formation may be critical. The BHs grow exponentially during the merging process, releasing a total feedback energy $E_{\rm feed} \approx \epsilon_{\rm f} M_{\rm BH} c^2$ as thermal input into the surrounding gas over a short time-scale, where $\epsilon_{\rm f}$ is the fraction of binding energy released by gas accreted on to the BH and deposited as feedback, and c is the speed of light. If modeled with a Hernquist profile (Hernquist 1990) with scale length a, the binding energy of a spheroidal component with mass M can be estimated as $E_{\rm bind} = -GM^2/6a$, where G is the gravitational constant. In terms of the projected velocity dispersion, this energy is $E_{\rm bind} \approx 1.6 M \langle \sigma^2 \rangle$, where the quantity $\langle \sigma^2 \rangle$ is averaged within an effective radius of the spheroid. Using the observed approximate scaling (Magorrian et al. 1998; Marconi & Hunt 2003) between the BH mass and spheroid mass, $M_{\rm BH}/M \sim 0.005$, the ratio of feedback energy from BH accretion to spheroid binding energy is typically

$$\left| \frac{E_{\rm feed}}{E_{\rm bind}} \right| \gtrsim 10 \left(\frac{\epsilon_f}{0.005} \right) \left(\frac{\langle \sigma \rangle}{300 {\rm km\ s^{-1}}} \right)^{-2}. \quad (1)$$

The feedback energy from BH accretion can then greatly exceed the binding energy of the spheroid, supplying ample energy to affect the bulge component of remnant systems.

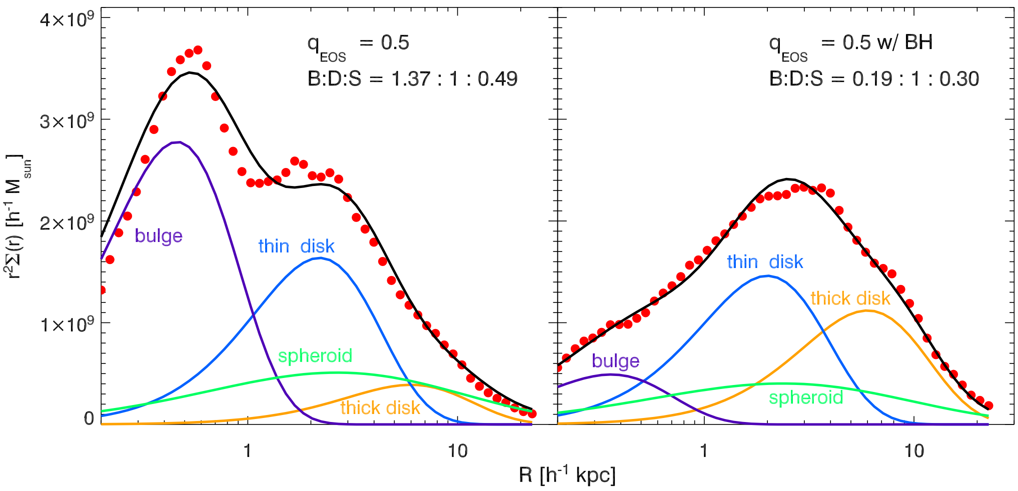

FIG. 3.— Remnant stellar mass surface density for a moderately pressurized ($q_{\rm EOS}$ = 0.5) ISM, without (left) and with (right) black hole feedback. Shown is the measured stellar surface density (dots), and bulge (purple line), thin disk (blue line), thick disk (orange line), spheroid (green line), and composite (black line) mass models fits. We fit exponential disks to the central bulge and stellar disk components, and a de Vaucouleurs (1948) profile to the stellar spheroid. The vertical structure of the remnant is also well fitted by our four component model, and assuming a vertical sech$^2(z)$ profile for the stellar disks we find evidence for two components with different scale heights that we label as thin and thick disks. We also report the relative size of the bulge (B), thick + thin disk (D), and spheroid (S) components for each remnant. The simulation with black hole feedback produces a central bulge component a factor $\sim 6\times$ less massive than in the simulation without black holes.

Combined with the effects of ISM pressurization, the powerful energetics of feedback from accreting supermassive BHs may provide the crucial missing ingredient to the formation of disk galaxies in the ΛCDM cosmology by helping galaxies resist the destructive nature of hierarchical structure formation. Our results therefore differ substantially from previous merger simulations that neglected star formation and supernova feedback (Barnes 2002) or feedback from black hole accretion (Kazantzidis et al. 2004). The observed $M_{\rm BH}-\sigma$ relation finds a new and unexpected connection to the formation of spiral galaxies as BH feedback, in setting the size of the bulge component during a merger, increasing the vitality of remnant stellar disks. As the merger-driven scenario for disk formation relies on a large gas fraction in the progenitor systems, the frequent gas-rich mergers at high ($z > 2$) redshifts may spawn primitive spiral galaxies. Finally, to confirm the merger-driven scenario for disk galaxy formation as a viable supplement to the dissipational collapse model, cosmological simulations of galaxy formation, including pressurized multiphase ISM physics and feedback from supermassive BH growth, should be performed at sufficient resolution to determine the importance of BH feedback to the cosmological frequency of disk galaxies. While cosmological simulations of galaxy formation with multiphase ISM physics appear promising (Robertson et al. 2004), the inclusion of BH feedback will provide a more comprehensive picture of cosmological disk galaxy formation.

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