Excitation of Activity in Galaxies by Minor Mergers

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ABSTRACT

Mergers between gas–rich disks and less–massive dwarf galaxies are studied using numerical simulation. As the orbit of a satellite decays through dynamical friction, the primary disk develops large-amplitude spirals in response to its tidal forcing. While these features arise in both the stars and the gas in the disk, the non–axisymmetric structures in the gas differ slightly from those in the stars. In particular, as a consequence of the formation of strong shocks in the gas and the effects of radiative cooling, the gas response tends to lead the stellar response, enabling the stars to strongly torque the gas. These torques deprive the gas of its angular momentum, forcing a significant fraction of it into the inner regions of the disk. Depending on the detailed treatment of the gas physics and the structure of the primary galaxy, the gas can also condense into dense knots in reaction to the gravitational perturbation of the dwarf, which later sink to the center of the primary by dynamical friction against the stellar background.

The radial inflows induced by these mergers accumulate large quantities of interstellar gas in the nuclear regions of the host disks. In some cases, nearly half of all the gas initially distributed throughout the disk winds up in a dense “cloud” several hundred parsecs in extent. The models reported here do not include star formation and, so, we cannot determine the ultimate fate of the gas. Nevertheless, given the high densities in the nuclear gas, it is plausible to identify these concentrations of dense gas in the remnants with those accompanying intense starbursts in some active galaxies. Therefore, the calculations here provide a framework for interpreting the origin of nuclear activity in otherwise quiescent disk galaxies. To the extent that galaxy formation is a chaotic process in which large structures are built up by the accretion of smaller fragments, our models may also be relevant to starbursts and the onset of nuclear activity in proto–galaxies at high redshifts.

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1. Introduction

A large fraction of all galaxies are inferred to exhibit unusually high rates of star formation within their central regions. The most spectacular examples of this phenomenon are the so-called ultraluminous infrared galaxies, discovered originally by the IRAS observatory (e.g. Soifer et al. 1984a,b), some of which have infrared luminosities well in excess of $10^{12} L_\odot$ (for a review, see Soifer, Houck & Neugebauer 1987). While rare, the ultraluminous IRAS galaxies are now thought to be the dominant population of extragalactic sources at infrared luminosities $L_{\text{ir}} > \sim 10^{11.3} L_\odot$ and are more common than quasars having corresponding bolometric luminosities $L_{\text{bol}} \sim 10^{12} L_\odot$ (e.g. Soifer et al. 1987; Soifer et al. 1989; Scoville & Soifer 1991; Sanders et al. 1991; Sanders 1992).

It is generally believed that the luminous infrared galaxies are powered by unusually high rates of star formation in their nuclei, although some have spectra reminiscent of active galactic nuclei and may well contain buried “monsters.” (See, e.g. Sanders et al. 1988ab, Carico et al. 1990, Condon et al. 1992.) Supporting the starburst model are ground–based surveys which indicate that these objects are typically rich in molecular gas (e.g. Young et al. 1984, 1986; Sanders & Mirabel 1985; Sanders et al. 1987) and that more than 50% of the gas is usually concentrated within nuclear regions less than one kpc in radius (e.g. Scoville et al. 1986; Sargent et al. 1987, 1989; Sanders et al. 1991; Tinney et al. 1990; Scoville et al. 1991). For example, Arp 220 has an infrared luminosity of $1.5 \times 10^{12} L_\odot$ and a nuclear concentration of gas a few hundred parsecs in radius containing of order $2 \times 10^{10} M_\odot$ of molecular gas (see, e.g. Scoville 1992).

While the origin of these ultraluminous IRAS galaxies is not entirely clear, a consensus has emerged that these sources are triggered by collisions involving at least one gas–rich disk galaxy. This suggestion appears especially firm for the brightest IRAS galaxies, which invariably display telltale signs of mergers, such as multiple nuclei, tidal tails, loops, and shells (e.g. Allen et al. 1985; Joseph & Wright 1985; Armus et al. 1987; Sanders et al. 1988a,b; Kleinmann et al. 1988; Sanders 1992). Self–consistent numerical models support this notion and demonstrate that the gravitational torques attending the merger of two gas–rich disks are capable of driving a large fraction of all the gas to the center of the merger remnant (e.g. Negroponte & White 1983; Noguchi 1991; Barnes & Hernquist 1991), which may fuel intense star formation (Mihos et al. 1991, 1992; Mihos 1992; Mihos & Hernquist 1994a,b). The amounts of gas involved, the final distribution of this gas in the remnant nucleus, and the time–scales over which it is driven to the center of the remnant are all in accord with constraints derived from observed properties of infrared–luminous galaxies.

While “major” mergers of comparable–mass spirals are the most striking example of galaxy collisions, they are less common than “minor” mergers of satellites or dwarfs with larger galaxies. Indeed, simple estimates employing Chandrasekhar’s (1943) description of dynamical friction show that the typical galaxy, irrespective of type, has probably accreted at least several 10’s of percents of its mass in the form of discrete subunits (Ostriker & Tremaine 1975; Tremaine 1981). This is to be contrasted with the situation for major mergers, which leave remnants structurally akin to
ellipticals (e.g. Barnes 1988, 1992), implying that at most 20% of all galaxies have experienced a bona fide major merger event, assuming that all present-day ellipticals formed in this manner. While it is beyond the scope of the present discussion to debate the merits and faults of the “merger hypothesis” (Toomre & Toomre 1972; Toomre 1977), it seems likely that not all ellipticals originated in major mergers. If so, then minor mergers are at least an order of magnitude more common than major mergers, averaged over the age of the universe. It should be noted, however, that these estimates are subject to considerable uncertainty (see, e.g. Hernquist 1991a, 1993a); nevertheless, they admit the possibility that minor mergers have played a dominant role in shaping all galaxy types, a viewpoint supported by models in which galaxy formation is not a smooth process (e.g. Searle & Zinn 1978; Dubinski & Carlberg 1991; Katz & Gunn 1991; Katz 1991, 1992).

N–body simulations demonstrate that minor mergers can drive structural evolution in disks without completely destroying them (Quinn & Goodman 1986; Quinn et al. 1993). Among the properties of disk galaxies which have been attributed to minor mergers are warps in stellar disks (e.g. Quinn et al. 1993), kinematic anomalies in galaxy halos (e.g. Larson 1990), dynamical heating of disks (Toth & Ostriker 1992) and the origin of “thick” disks (e.g. Carney et al. 1989; Quinn et al. 1993; Walker et al. 1994a), structural peculiarities of some bulges (e.g. Hernquist & Quinn 1989), and the origin of “amorphous” disk galaxies (e.g. Hernquist 1989). (For a recent review, see Majewski 1993.)

In fact, the nature of galactic disks following accretion events has prompted the suggestion (e.g. Schweizer 1986, 1990) that minor mergers may contribute to the formation of S0 galaxies, particularly those having “X-structures” (Walker et al. 1994b). However, aside from issues such as spheroid building and disk survival, minor mergers must also explain differences in the gas content between late-type disk galaxies and S0’s in this scenario. While S0 disks contain widely varying amounts of gas, they are typically gas–poor in relation to late–type disk galaxies (Thronson et al. 1989; Bregman et al. 1990), and display little or no spiral structure. Therefore, an understanding of the evolution and final fate of the ISM in satellite mergers is needed to judge this “minor merger hypothesis” for building S0 disks.

If many occurrences of starbursts in galaxies are triggered by mergers between galaxies, as suggested by the IRAS discoveries, then it is natural to inquire whether or not satellite accretions could produce similar effects. Hernquist (1989, 1991b) examined this possibility using a hybrid N–body/hydrodynamics code to follow the response of disks containing both stars and gas to the tidal forcing of cannibalized satellites. His models demonstrate that the two components react differently to the gravitational torques induced by the dwarf, ultimately driving large amounts of gas to the center of the disk. These findings are qualitatively similar to those obtained later by Barnes & Hernquist (1991), and also those of Noguchi (1987, 1988, 1991) and Noguchi & Ishibashi (1986) who studied transient encounters between self–gravitating disks and external perturbers represented as rigid potentials. However, Hernquist (1989) considered only a limited range of parameters and was not able to determine if the effect is generic to accretion events.
In this paper, we extend the computations of Hernquist (1989, 1991b) by employing more physical models and by considering a range of structural parameters for the merging galaxies. Our results indicate that while the tendency of tidal torques to promote radial gas inflows during accretion events does not depend sensitively on the microphysics used in the simulations, the structure of the primary galaxy is critical and the strength of the inflow and ensuing starburst are affected by, e.g., whether or not the primary contains a dense, central bulge (Mihos & Hernquist 1994b,d). Unfortunately, the computational expense of calculations like those reported here makes it impractical to study a large region of parameter space. Nevertheless, our results reinforce the notion that galaxy collisions, in particular minor mergers, play an important role in triggering unusual activity in galaxies, but that this role may vary among galaxy types and may have been particularly significant at earlier phases of galaxy evolution, assuming that disks formed before most bulges.

2. Methods

2.1. Evolution Code

The simulations described here were performed with a hybrid N–body/hydrodynamics code for evolving composite systems of collisionless matter and gas (Hernquist & Katz 1989). Gravitational forces are computed with a hierarchical tree algorithm (Barnes & Hut 1986), optimized for vector architectures (Hernquist 1987, 1990b), with a tolerance parameter, \( \theta = 0.6 \), including terms up to quadrupole order in the multipole expansions.

Gravitational forces are softened using a cubic spline (Goodman & Hernquist 1991), with different types of particles having different softening lengths (Barnes 1984, 1985a,b). In the models described below, disk, halo, and bulge particles have softening lengths \( \epsilon_d = 0.08 \), \( \epsilon_h = 0.37 \), and \( \epsilon_b = 0.06 \), respectively, in the dimensionless units defined in §2.2. These values were chosen so that the softening length of each species is nearly equal to the mean-interparticle separation at the half-mass radius of each component. We tested the integrity of this choice by performing simulations of isolated disks in which a softening length \( \epsilon = 0.08 \) was used for all components, which enabled us to select an appropriate timestep for experiments in which different softening lengths were used for the various species. From these test calculations we found that employing slightly larger values of \( \epsilon \) for the coarsely-resolved components (the disk and halo) mitigates two-body effects relative to simulations in which all particles interact via the softening length assigned to the most finely resolved component.

A Lagrangian technique known as smoothed particle hydrodynamics (SPH; e.g. Lucy 1977; Gingold & Monaghan 1977; Monaghan 1985, 1992) is used to model the disk gas. In this approach, gas is partitioned into fluid elements which are represented computationally as particles. These
particles obey equations of motion similar to the collisionless particles used to represent the stars and dark matter, but include terms to describe local effects in the fluid, such as pressure gradients, viscous forces, and radiative heating and cooling. The implementation we use is similar to that given in Hernquist & Katz (1989). In particular, the SPH particles have their own time–steps, as determined by the Courant condition (Monaghan 1992; Hernquist & Katz 1989, eq. 2.37), with Courant number $C = 0.3$. A conventional form of artificial viscosity is employed (Hernquist & Katz 1989; their eqs. 2.22 and 2.23), with the parameters $\alpha = 0.5$ and $\beta = 1.0$.

As in Hernquist & Katz (1989) the SPH particles in our models have their own smoothing lengths, to optimize the range in spatial scales resolved by the code. The smoothing lengths are specified by requiring that each SPH particle have a certain number of neighbors, $N_s$, within a volume of radius two smoothing lengths, and smoothed estimates are symmetrized to preserve momentum conservation in the manner described by Hernquist & Katz (1989; their eq. 2.16).

The best choice of $N_s$ is somewhat controversial. A smaller value implies that smaller scales can be resolved, but at the expense of introducing larger errors in the local estimates of smoothed quantities such as the density. Previous calculations similar to those discussed here generally employed $N_s \approx 30$ (e.g. Hernquist 1989, 1991b; Barnes & Hernquist 1991, 1992a; Hernquist & Barnes 1991). However, empirical and analytic studies of error propagation in SPH suggest that larger values are preferable for higher accuracy (e.g. Rasio & Shapiro 1991; Rasio 1991; see, also Hernquist 1993d). In deference to these analyses, we have chosen to employ $N_s = 96$ in the calculations here, although it should be noted that our present results are in essential agreement with the earlier ones using smaller values of $N_s$.

Several modifications were incorporated into the original TREESPH code of Hernquist & Katz (1989) for our application. From a comparison of simulations employing an explicit treatment of radiative heating and cooling in the gas with others using an isothermal equation of state (Barnes & Hernquist 1994), we opted to maintain the gas in the models here at a fixed temperature. Owing to limitations imposed by mass resolution with a finite number of particles, we are unable to accurately describe the structure of a multi–phase medium, as in more realistic models of the interstellar medium in galaxies (e.g. McKee & Ostriker 1977). Hernquist (1989) skirted this issue by inhibiting radiative cooling below some cut–off temperature, $T_c$, suppressing the formation of dense clumps of cold gas. For $T_c \sim 10^4$ K, most of the gas in his models and that in those of, e.g., Barnes & Hernquist (1994) resides close to this cut–off, owing to the short radiative cooling time–scales of interstellar gas. As a result, simulations with an isothermal equation of state differ little from those employing a more “realistic” treatment of the gas physics. The approach chosen here, i.e. requiring the gas to remain at a constant temperature, simplifies the interpretation of the results and enables us to infer the effect of varying a single parameter on the evolution of the system. (For a discussion, see e.g. Barnes & Hernquist [1992b, 1993] and for details, see e.g. Barnes & Hernquist [1994] and Mihos & Hernquist [1994b].)

The equations of motion are integrated using a time–centered leap–frog algorithm (e.g. Press
et al. 1986). The collisionless particles are integrated on a single, fixed time–step of $\Delta t = 0.16$ in models without bulges and $\Delta t = 0.08$ when bulges are included (see Hernquist 1992, 1993c). Scaled to values appropriate for the Milky Way, these correspond to physical times of roughly $2 \times 10^6$ and $10^6$ years, respectively. The SPH particles are allowed to have time–steps smaller than this by factors of powers of two in order to satisfy the Courant condition. In the most extreme cases we considered, some gas particles had time–steps as small as 1/128–th of the large system time–step for brief intervals during the simulations. For an isothermal equation of state, the total system energy is not conserved since it is assumed that heat generated by adiabatic compression and shocks is immediately lost from the system. Even so, the total energy was usually conserved to about 1% accuracy, and from simulations employing an ideal gas equation of state with an explicit treatment of radiative heating and cooling, in which energy losses can be monitored, we infer that integration errors in our models result in an error in energy conservation at the level of 0.1%.

2.2. Galaxy Models

The approach used to construct stable galaxy models consisting of several distinct, interacting components, is described in detail by Hernquist (1993b). Unlike the technique employed by Hernquist (1989, 1991b), our method permits us to include the self–gravity of the halos and bulges of the galaxies, rather than modeling them by rigid potentials. The self–gravity of the halos, in particular, contributes significantly to the torque responsible for the orbital decay of the merging objects (Walker et al. 1994a)

As in previous studies which did not include gas (Hernquist 1992, 1993c), the primary galaxies in our simulations include exponential disks of stars, which initially follow the density profile

$$\rho_d(R, z) = \frac{M_d}{4\pi h^2 z_0} \exp(-R/h) \operatorname{sech}^2 \left( \frac{z}{z_0} \right),$$

where $M_d$ is the disk mass, $h$ is a radial scale–length, and $z_0$ is a vertical scale–thickness. These disks are embedded in self–consistent “dark” halos, which have density profiles

$$\rho_h(r) = \frac{M_h}{2\pi^{3/2} r_c^3} \frac{\alpha \exp(-r^2/r_c^2)}{r^2 + \gamma^2},$$

where $M_h$ is the halo mass, $r_c$ serves as a cut–off radius, $\gamma$ is a “core” radius, and $\alpha$ is a normalization constant defined by

$$\alpha = \left[ 1 - \sqrt{\pi q} \exp(q^2) \left( 1 - \operatorname{erf}(q) \right) \right]^{-1},$$

where $q = \gamma/r_c$. The abrupt truncation of the halos as $r \to r_c$ is not intended to be a realistic description of the matter distribution in actual galaxies, but enables us to construct objects.
having plausible rotation curves in regions dominated by the luminous material, without requiring the investment of large amounts of computer resources to follow the trajectories of loosely bound particles at large radii. The particles used to represent the disk gas follow roughly the same density profiles as the disk stars, equation (2.1), but their vertical scale–height depends on the temperature of the gas and $R$. For a gas temperature $T = 10^4$ K, the gas layer is thinner than the stars for vertical stellar dispersions similar to the Milky Way.

In some cases, we include optional bulges in the primary galaxies, using an oblate form of the potential–density pair proposed by Hernquist (1990a) for spherical galaxies and bulges:

$$\rho_b(m) = \frac{M_b}{2\pi a c^2} \frac{1}{m(1 + m)^3}$$  \hspace{1cm} (2.4)

where $M_b$ is the bulge mass, $a$ is a scale–length along the major axis, $c$ is a scale–length along the minor axis, and

$$m^2 = \frac{x^2 + y^2}{a^2} + \frac{z^2}{c^2}.$$  \hspace{1cm} (2.5)

(See, for example, Dubinski & Carlberg 1991.)

Particles are distributed in space according to the density profiles specifying the structure of each component included in a particular model. Particle velocities are initialized using moments of the Vlasov equation and by approximating the velocity distributions by Gaussians (Hernquist 1993b).

In what follows, we express physical quantities in dimensionless units in which the gravitational constant, $G = 1$, the disk exponential scale–length, $h = 1$, and the disk mass, $M_d = 1$. If we relate these to the properties of the Milky Way suggested by photometric and kinematic studies (e.g. Bahcall & Soneira 1980; Caldwell & Ostriker 1981), i.e. $h = 3.5$ kpc and $M_d = 5.6 \times 10^{10} M_\odot$, then unit time and velocity are $1.31 \times 10^7$ years and 262 km/sec, respectively.

The results presented in §3, which describe in detail a minor merger between a gas–rich disk and a smaller companion, employed a galaxy model not having a bulge and whose stellar disk and halo parameters are $z_0 = 0.2$, $M_h = 5.8$, $\gamma = 1$, and $r_c = 10$. The Toomre $Q$ parameter (Toomre 1963) varies weakly with radius in these models; we normalize it so that for the stars $Q = 1.5$ at a solar radius, $R_\odot = 8.5/3.5$. In this model, the gas comprises 10% the total mass of the disk; i.e. the stellar disk has a mass of 0.9 and the disk gas has a mass of 0.1 in our dimensionless system of units. For a temperature of $10^4$ K, the gas particles are distributed initially with the density profile of equation (2.1) but with a vertical thickness depending on $R$. If an isothermal equation of state is adopted, the vertical width of the gas layer increases with distance from the center of the galaxy. This effect is included in an approximate manner when the disk is created and small departures from the actual vertical profile mostly dissipate on a vertical sound–crossing time once the galaxy is allowed to evolve.

Figure 1 shows the result of a time–integration of one of these galaxy models in isolation. In this example, the luminous matter comprises stellar and gas disks of mass 0.9 and 0.1, respectively.
A total of 32,768 particles represent each of the two collisionless components, \textit{i.e.} the disk and the halo, and 16,384 SPH particles describe the interstellar gas. In this case, the gas was taken to be isothermal with a temperature $T = 10^4$ K. As is evident from Figure 1, the disk rapidly develops a spiral pattern that persists throughout the time period covered by the simulation. This structure probably results from the swing-amplification of noise in the potential by the disk (Toomre 1981, 1990), although there are indications that this explanation may not be complete (\textit{e.g.} Sellwood 1989a). We are encouraged that our models are well-behaved over the timescales needed to study satellite accretions like those discussed below. In particular, the disks are stable and do not develop spontaneous inflows of gas. Over much longer timescales, however, the models are bar-unstable owing to discreteness noise in the halo potential which can be amplified by the disk (Sellwood 1989b). This effect is negligible for the simulations described in §§3 and 4, but complicates efforts to investigate orbital decay from polar and retrograde orbits (Walker \textit{et al.} 1994a).

2.3. Satellite and Encounter Parameters

The satellite galaxies in our simulations are represented by spherical versions of the model given by equations (2.4) and (2.5). Our fiducial simulation, described in §3, employed a satellite with mass $M_{\text{sat}} = 0.1$ and scale-length $a = 0.15$, so that its mean half-mass density is roughly the same as the mean density of disk material in the same volume near the center of the primary. This choice ensures that some portion of the satellite will survive to the center of the disk in cases where orbital decay occurs rapidly. The mass distribution of the satellite is truncated so that it is initially within its tidal radius. We also ran models with either more massive or denser satellites; the results of these calculations are discussed in §4.

Initially, the dwarfs are placed on circular orbits at 6 scale-lengths from the center of the primary. We ran smaller calculations varying the size of the orbit and the results were qualitatively similar to those described here, but required longer integrations in cases where the satellite’s orbit was more extended. We also varied the inclination of the orbit plane. In the models described in detail below, the orbit plane is initially inclined relative to the disk by 30 degrees, and the satellite orbits in a prograde manner. Polar and retrograde orbits require prohibitive amounts of cpu time for the mass ratios we consider (see Walker \textit{et al.} 1994a). Less-inclined orbits decay slightly more rapidly; the qualitative outcome is similar to mildly inclined orbits.

Clearly, the assumption of a circular orbit is not entirely realistic, given the eccentricities of the Milky Way’s companions. Our choice is motivated by practical considerations which force us to consider mergers which occur rapidly. More sophisticated approaches for computing the self-gravity of the interaction and the use of parallel hardware may make it possible to examine a wider set of parameters in the near future.
3. Galaxy Models

In this section we describe the outcome of a merger between a primary galaxy consisting of a disk and dark halo and a satellite companion. The parameters were chosen to resemble the encounter reported by Hernquist (1989), but here we include the full self-gravity of each component.

3.1. Overview of Merger Dynamics

Figure 2 presents a set of face-on images of the merger. Owing to dynamical friction against the disk and the halo, the orbit decays rapidly and the satellite sinks to the center of the disk within only a few orbital periods; the entire time-period displayed in Figure 2 spans roughly $1.2 \times 10^9$ years. In response to tidal torques from the dwarf, the primary disk exhibits large-amplitude non-axisymmetries that are particularly striking at intermediate times between $t \approx 30$ and $t \approx 70$. At no time does the disk develop an extended bar, although the structures are linear in appearance near the center. As usual, the regions leading the satellite are mostly devoid of material because of the gravitational perturbation exerted on stars there by the dwarf (Quinn & Goodman 1986). Once the merger is complete, the disk supports some weak spiral structure that eventually mixes away, in contrast to the longer-lived features present in isolated disks, like those shown in Figure 1.

Figure 3 shows an edge-on view of the encounter. As has been noted previously (Quinn & Goodman 1986; Quinn et al. 1993), the satellite sinks first into the disk plane before plunging into the center of the primary, warping the outer parts of the disk. Depending on the shape of the halo, these warps can persist for a significant fraction of a Hubble time before they are washed out by phase-mixing (Quinn et al. 1993; Dubinski 1994). The inner parts of the disk are heated vertically, increasing its thickness and the vertical dispersion of stars there. The characteristics of post-merger stellar disks like that in Figure 3 are compared with observed properties of thick galactic disks by Quinn et al. (1993) and Walker et al. (1994a) who argue that accretion events are a viable mechanism for producing these features.

Viewed from afar, the gas in the disk behaves qualitatively like the stars do, as can be seen in Figure 4. The spirals which develop in the gas are crisper than their stellar analogues, however. This effect, together with the time-dependent nature of the tidal field, allows the stellar response to torque the gas, forcing much of it into the center of the disk.

Material stripped from the satellite during its plunge through the disk forms both leading and trailing “streamers” which eventually wind up to resemble a spiral feature, as can be seen in Figure 5. This pattern is kinematic, transient in nature, and fades completely in a few orbital
periods beyond the last frame shown in Figure 5. For the choice of parameters in this model, roughly 40% of the satellite material sinks to within one scale-length of the disk center. At late stages of the encounter, however, a dense blob of gas accumulates in the middle of the disk which completely disrupts the dwarf during the final stages of the merger, in a manner analogous to that in the model of Hernquist (1989).

The final stages of the merger are illustrated in Figure 6, which shown the gas in the inner parts of the disk, magnified ten times relative to the images in Figure 4. As the dwarf approaches the central regions of the disk, the non-axisymmetric response dominates both the gas and stellar distributions. Near the center, this response takes the form of a linear feature which resembles a bar and which is clearly visible by \( t = 53.6 \) in Figure 6. As the dwarf plunges into the center, the gas in this feature is forced onto self-intersecting orbits which dissipate its kinetic energy by forming shocks. The internal energy added to the gas is radiated away immediately, with our assumption of an isothermal equation of state. (The results are not changed qualitatively if an ideal equation of state is used together with a more physical description of radiative cooling, owing to the short cooling times of the gas in this region [Barnes & Hernquist 1994].) Because of this rapid dissipation of energy the response of the gas differs from that of the stars, which are not required to follow closed orbits. As we show in §3.2, this difference is such that the stars torque the gas, removing its angular momentum, and allowing it to flow rapidly into the center of the primary.

Figure 7 shows mass profiles of the gas at various stages during the merger. By the time of the final panel in Figure 6 the collapse of gas into the center is essentially complete. As can be inferred from Figure 7, by the end of the sequence shown in Figure 6, approximately 45% of the gas initially spread throughout the disk has collapsed into a region only a few hundred pc across, when scaled to the values given in §2.2. The detailed structure of this nuclear accumulation of gas is not accurately modeled by our simulations because of gravitational softening. Nevertheless, the gas densities in this region are sufficiently high, in principle, to trigger intense starburst activity (Mihos & Hernquist 1994b).

The onset of the catastrophe shown in Figures 6 and 7 is accompanied by the tendency of cool gas in our models to fragment on small scales under its own self-gravity in regions containing self-intersecting flows. Evidence for this effect is clearly visible at intermediate times in Figure 6, between \( t = 53.6 \) and \( t = 60.0 \). However, as discussed further in §4, the radial inflows are virtually unaffected if the gas temperature is raised to inhibit fragmentation or if the self-gravity of the gas is explicitly ignored, essentially preventing the gas from breaking apart into clumps. These findings support the view of Noguchi (1988) who argued that the self-gravity of the gas plays an unimportant role in the onset of tidally induced nuclear gas flows in disks. In §§3.2 and 4.1, we discuss physical mechanisms responsible for the outcome shown in Figures 6 and 7.
3.2. Angular Momentum Transport & Torques

The physical nature of the nuclear gas inflow in our fiducial model can partly be understood by examining the evolution of the angular momentum of the gas driven to the center of primary during the merger (Barnes & Hernquist 1994). In Figure 8, we show the orbital, spin, and total angular momentum of the halo (panel a), the disk stars (panel b), the gas which accumulates in the nucleus (panel c), and the portion of the satellite which sinks to within one scale-length of the center (panel d). The quantities shown were computed in the manner described by Hernquist (1992).

As in all such events, the orbital angular momentum of the merging galaxies is efficiently converted into spin angular momentum of the various components through tidal torquing. From panel (d) of Figure 8, it can be seen that the orbital angular momentum of the dwarf decays monotonically. In response, the halo and stellar disk are spun up (as seen in Figures 8(a) and 8(b)), accepting comparable amounts of the satellite’s orbital angular momentum. Following its disruption by the gas cloud at the center of the disk, the satellite debris acquire a small amount of spin angular momentum as its remains are incorporated into a diffuse ring orbiting the nucleus (see, e.g. Figure 3 of Hernquist 1989).

The angular momentum of the gas deposited into the center of the disk declines monotonically until \( t \approx 80 \), after which it remains nearly constant as the inner regions of the disk settle into a new equilibrium. As can be seen from panel (c) of Figure 8, the angular momentum of this gas has declined by nearly two orders of magnitude during the merger, enabling it to accumulate on the scales shown in Figure 7. This loss of angular momentum is most rapid during the stages of the encounter shown in Figure 6.

To interpret the loss of angular momentum by the central gas accumulation, we identified the particles in this object when the merger was complete and computed the various torques on this group of particles during the course of the merger. Figure 9 shows the time evolution of the torque on this gas. In panel (a), the magnitude of the full torque on the gas is compared with the rate of change of its internal (spin) angular momentum. The two curves track each other quite well, proving that the gas loses angular momentum in response to its physical torquing rather than, for example, as the result of numerical errors. Small differences between the solid and dotted curves in panel (a) are consistent with inaccuracies expected in estimating \( |ds/dt| \) from data that are somewhat coarsely sampled in time.

Panel (b) of Figure 9 compares the gravitational torque acting on the gas, indicated by the dashed curve, with the hydrodynamical torque, shown as the dotted curve. Clearly, the hydrodynamical contribution to the torque is negligible compared with the gravitational torque throughout the merger, in agreement with similar findings by Barnes & Hernquist (1991) and Barnes & Hernquist (1994) for gas flows induced by major mergers. This does not mean that hydrodynamical effects are unimportant to the dynamics, however. As we emphasize in §5, shock
heating and radiative cooling are responsible for the differences in the dynamics of the gas relative to that of the disk stars, which is precisely why gas is driven to the center of the remnant. This point is made plausible by panel (c) of Figure 9 which shows the gravitational torque on the gas, broken down by mass component. The torque is always dominated by its contribution from the disk stars, rather than that directly from the satellite. In fact, since in the final stages of the accretion the orbital phase of the dwarf tends to lead the gas response, the direct effect of the satellite on the gas is to torque it up, averaged over time. The halo also plays a mostly negligible role in removing angular momentum from the gas. Only during the final stages of the encounter is its influence at all significant, and even then its contribution to the full torque amounts to less than 25%.

Not surprisingly, the gravitational torque on the central gas from the disk stars is dominated by material in the inner portions of the disk. This is illustrated in panel (d) of Figure 9, where the gravitational torque from the disk is broken down into its contributions from stars in quartiles of the initial mass distribution. The torque from the innermost two quartiles is clearly much greater than that from outlying regions and, so, it is the matter within the initial half-mass radius of the disk that is mostly responsible for torquing the gas and removing its angular momentum.

It is also of interest to determine the dominant azimuthal wavenumber of the disk response that determines the torque on the gas driven to the center of the remnant. Figure 10 shows the power in the lowest non-axisymmetric modes in the inner half mass of the stellar disk as a function of time during the merger. The structure is always dominated by an $m = 2$ response. Higher order modes are nearly always unimportant, except at late times when a three-armed spiral ($m = 3$) evidently plays a small, but not entirely negligible role. It is reassuring, but not unexpected, that the amplitude of the non-axisymmetric disk response peaks at times when the torque on the gas is a maximum, as can be seen by comparing Figures 9 and 10. The exact nature of the $m = 2$ disk response is a bit difficult to characterize. Throughout most of the encounter, the disk is highly distorted and sports a pair of well-defined spirals. At late stages, the response near the center is linear in appearance, although this “bar-like” distortion is not reminiscent of bars in actual spirals owing to its short lifetime and extent.

4. Other Models

In spite of some differences in the details of the simulations, the results of our fiducial model are in good agreement with the findings of Hernquist (1989), as discussed in §5. In his earlier study, however, Hernquist made no attempt to vary numerical parameters or those defining the structures of the merging galaxies. Below, we describe our attempts to explore interesting regions of parameter space, based on 20 or so additional models.
4.1. Variation in Gas Temperature

For simplicity, we chose to employ an isothermal equation of state in the calculations reported here. Requiring the gas to remain at a fixed temperature is equivalent to demanding that it radiatively heat and cool at well-defined rates. A higher gas temperature thus corresponds to slightly less efficient cooling.

We investigated the sensitivity of the results described above to the temperature of the gas by running four calculations identical in all respects to our fiducial model, but employing gas temperatures \( T = 3 \times 10^3, 3 \times 10^4, 10^5, \) and \( 3 \times 10^5 \) K. Qualitatively, the outcomes were similar to our fiducial model, except for the simulation with a \( T = 3 \times 10^5 \) K gas, which exhibited substantially less gas inflow than the others. At intermediate stages of the merger, however, the detailed structure of the gas in the disk depends sensitively on its temperature. This effect is illustrated in Figures 11 and 12 which are identical to Figure 6, but for the models with \( T = 3 \times 10^3 \) and \( T = 10^5 \) K gases, respectively.

The cooler gas has a greater tendency to fragment under its own self-gravity in regions supporting flows that self-intersect. This trend is obvious in Figure 11, where a number of distinct fragments form in the gas by \( t \approx 57.6 \) which eventually sink to the center of the disk and coalesce. In the evolution summarized in Figure 11, several of the fragments are sufficiently massive that the dynamical friction they experience is adequate to drive them to the disk center. We emphasize that this effect is driven by the response of the disk to the tidal forcing of the dwarf and does not occur in our isolated models over the temperature range we examined, as we verified by running a counterpart to the simulation in Figure 1 with a 3000 K gas.

For higher gas temperatures, the fragmentation process just described is inhibited, as can be inferred from Figure 12. The appearance here is much smoother than that in Figure 6 or especially that in Figure 11. Also, as suggested by the frame at \( t = 81.6 \), the physical mechanism which enables the disk stars to torque the gas is more evident. During the final stages of the merger, the potential near the center of the disk changes rapidly owing to the contribution from the satellite, whose orbit decays rapidly at this late time. The disk stars do not dissipate energy and so are less restricted in their choice of orbits than the gas, which must reside on closed orbits if it is not to dissipate energy. In a time-stationary potential that has a large non-axisymmetric component, gas can find closed orbits without dissipating a large fraction of its kinetic energy. In a potential which varies rapidly with time, as in Figure 12, however, the gas dissipates energy continuously since the family of closed orbits changes on the orbital decay timescale of the satellite. This results in significant shocking of the gas, as can be seen in Figure 12 at \( t = 81.6 \), and subsequent loss of energy by the gas as it instantaneously radiates away its excess internal energy, as required by the condition that it remain isothermal.

It is interesting that in spite of the differences in detail between Figures 6, 11, and 12 the amounts of gas driven to the center of the remnant and the final distributions of this gas are quite
similar. This is illustrated in Figure 13 which shows the final mass profiles of disk gas in the five simulations in which we varied the gas temperature. The quantity of gas driven to the center of the disk in the simulation employing a $T = 10^5$ K gas is only slightly less than in the runs with lower temperature gases. Evidently, however, the catastrophe can be inhibited if the gas is sufficiently hot, as can be seen from the curve in Figure 13 for the run with a $T = 3 \times 10^5$. We believe that this particular choice of equation of state is extreme, as implied by estimates of the temperature of diffuse gas in our own galaxy and the velocity dispersion of clouds.

There is a weak tendency for the warmer gas to form more diffuse accumulations in the centers of the disks, as can be inferred from Figure 14, where we plot the distributions of gas densities measured from the SPH particles in the various runs following the merger. Although the amounts of high density gas do not change significantly with increasing gas temperature, aside from the $T = 3 \times 10^5$ K case, the maximum gas density declines slowly but monotonically with increasing temperature. This results from the larger thermal support of the nuclear gas in the higher temperature models. Similar calculations employing an algorithm for converting the gas into stars (Mihos & Hernquist 1994d) imply, however, that this effect is not sufficient to prevent a strong starburst from occurring in the gas in all cases we have examined (again, aside from the model with $T = 3 \times 10^5$ K).

On the basis of Figures 13 and 14, we conclude that nuclear inflows of gas in disks accreting small satellites are relatively insensitive to details in the equation of state, provided that the gas can globally dissipate energy at roughly the same rate as that in the diffuse component of the ISM in our galaxy or as that in an ensemble of colliding clouds which maintain a velocity dispersion similar to the sound speed of a $10^4$ K gas. This latter claim is supported by the qualitatively similar nature of our results to those which have been obtained modeling the gas as a collection of discrete clouds (e.g. Negroponte & White 1983; Noguchi 1987, 1988, 1991).

### 4.2. Variation in Galaxy Structure

Of more immediate significance are the effects of varying the structure of the primary galaxy. To study this, we ran a set of models, identical in all respects to that described in §3, but including compact bulges in the primary. Here, we report on one of the simulations in detail. The bulge followed the density profile of equation (2.5) with $a = c = 0.2$ and $M_b = 1/3$, making the primary similar to those employed in the stellar-dynamical models of Hernquist (1993c). Unlike the rotation curve of the disk in our fiducial model, which rises slowly over the inner two scale-lengths of the disk (Hernquist 1992), the rotation curve of the model with this bulge climbs abruptly to within $\approx 75\%$ of its maximum and then to its peak over roughly two scale-lengths (Hernquist 1993c), in a manner similar to the rotation curves of typical early-type spirals.

Figure 15 shows the response of the stellar disk to the sinking satellite during the merger and
Figure 16 shows the response of the gas in the disk at the same times. Qualitatively, at this scale the merger appears similar to that shown in Figures 2 and 3. A frame-by-frame comparison shows, however, that the tidally induced structure in this new disk winds up more rapidly than that in our fiducial model. There is also a suggestion from the morphology that the non-axisymmetric features are slightly less well-defined than those in Figure 2. This is supported by a modal decomposition of the stellar disk, shown in Figure 17. A comparison with Figure 10 shows that while the non-axisymmetric response is again dominated by two-armed structures, the maximum power in the $m = 2$ mode is suppressed relative to that in the fiducial model, and this feature lives for a shorter period of time. In addition, the nature of the response has a slightly different visual appearance. While the inner regions of the disk with no bulge develop a linear, bar-like structure, the $m = 2$ mode in the disk in Figure 15 is morphologically like a wrapped spiral. Higher order modes are nearly absent in the new model.

The response of the gas on this scale is likewise similar in appearance to that in Figure 3; on smaller scales, however, it is dramatically altered. A magnified view of the gas in the inner portions of the disk is shown in Figure 18. Rather than sporting the linear bar-like feature shown in the fiducial bulgeless merger (Figure 6), the gas in this merger forms a tightly wrapped spiral, reducing the dissipation and inflow of gas into the very center of the primary disk. This is illustrated in Figure 19, where final mass profiles are shown for the run with the central bulge and our fiducial model which has no bulge. We also show one of our other simulations which included a less-massive bulge with mass $M_b = 1/9$. In this additional model, the bulge-scale length was chosen to be 0.14, so that the mean density was similar to that of the more massive bulge.

Figure 19 shows that the nuclear inflow is dramatically altered by changes in the mass distribution of the primary galaxy. Some gas is driven into the inner regions of the galaxies which include bulges, but both the amount of gas involved and the ultimate concentration of this gas are greatly reduced compared to our fiducial model. Evidently, the degree to which accretion events can induce activity in gas-rich spirals depends crucially on the structure of the primary galaxy.

The robustness of the apparent critical importance of the structure of the primary galaxy was examined by considering both denser and more massive satellite galaxies. These alterations did not promote more intense inflows of gas than those summarized by Figure 18 for models which included bulges. The presence of a dense central component appears to inhibit strong radial inflows of gas, and accompanying starbursts (Mihos & Hernquist 1994d), under rather broad circumstances. Clearly, if significantly less dense satellites were used they would be torn apart by tidal forces long before reaching the center of the disks and would therefore be unable to induce gas inflows of the type discussed above. In this sense, our results are determined by the relative structure of the primary and secondary galaxies.

4.3. Miscellaneous
We also checked the sensitivity of our results to the numerical parameters, such as the number of particles in the various components and those determining the magnitude of the artificial viscosity; no significant differences were found. Indeed, the results described in §3 are in good qualitative and quantitative agreement with those of Hernquist (1989), who used a smaller number of particles, a rigid halo, larger values for the parameters defining the artificial viscosity, a smaller value for $N_s$, and an explicit treatment of radiative heating and cooling of the gas, rather than an isothermal equation of state. Our inability to detect any dependence on the numerical parameters does not, of course, prove that we have obtained converged solutions, since we are able to vary, e.g. particle numbers by factors of only a few. Nevertheless, we are encouraged that our results appear to be relatively insensitive to what might be expected to be the physically most poorly constrained quantities, such as the artificial viscosity and SPH smoothing lengths.

To investigate Noguchi’s (1988) claim that the self-gravity of the gas is unimportant in triggering radial inflows of gas in tidally perturbed disks, we ran several calculations in which the self-gravity of the gas was ignored. One such model is reported by Hernquist (1991b). Our results confirm Noguchi’s suspicion to the extent that the onset of the catastrophe is relatively insensitive to this aspect of the dynamics. However, the ultimate distribution of the gas driven to the center of the disk, and hence the density distribution of the gas, are determined at least in part by the self-gravity of the gas. For example, in the simulation reported by Hernquist (1991b) roughly 50% of the gas in the disk was driven to a region $\approx 600$ pc across. The amount of gas involved is slightly greater than in the experiment reported in §3.1, since a more massive stellar disk was employed to maintain the same overall rotation curve for the galaxy, resulting in more efficient gravitational torquing of the gas by the stars. However, the resulting central gas concentration was more diffuse than in the experiment described in §3.1. In fact, this difference is hardly surprising, since the gas is essentially fully self-gravitating once significant amounts of it accumulate in the central portions of the primary galaxy.

We also varied the fraction of gas in the primary disk. The results described in §§3 and 4 were not qualitatively altered by these changes. Unfortunately, it is difficult to employ significantly larger gas fractions than those adopted here, because of the tendency of the gas to fragment when feedback from star formation is ignored. We expect that sufficiently detailed models would confirm our belief that disks with larger fractions of gas would be even more susceptible to tidally induced inflows than the simulations reported here.

Finally, we attempted to determine in detail why the presence of a dense bulge in the primary galaxy suppressed the gas inflow seen in our fiducial model, by using primaries with no bulges but with more compact halos, and hence more sharply rising rotation curves than in our canonical bulgeless galaxies. Unfortunately, the results were ambiguous. The collapse of gas into the center of the primary was similar to that seen in our fiducial model. However, this may have simply reflected the fact that we necessarily used a less massive halo than in the model describe in §3 to mimic the rotation curve of the model discussed in §4.2 which had a bulge with mass $M_b = 1/3$. In truth, our simulations are not well-suited for isolating the detailed dynamics responsible for the
outcomes seen because of the large number of free parameters defining each calculation.

5. Discussion

5.1. Comparison with Previous Work

The models analyzed and presented here are most closely related to those of Hernquist (1989), who also considered the accretion of less-massive companions by gas-rich disks. Although our new calculations differ considerably in detail from those of Hernquist (1989), our overall conclusions are similar to those expressed in this earlier study. In particular, we have reaffirmed the possibility that minor mergers can induce radial inflows of gas in galactic disks. In the case of our fiducial model, nearly 45% of all the gas initially spread throughout the disk collapses into a region several hundred parsecs across on a timescale of order a few hundred million years. As we show in a companion study (Mihos & Hernquist 1994c,d), if a plausible description of star formation is incorporated into the models, the gas densities in this region are sufficient to trigger an intense starburst lasting for $\sim 10^8$ years. As noted by Hernquist (1989), in principle this result eliminates worries over the observed mismatch between burst times $\sim 10^8$ years and galactic dynamical times $\sim 10^9$ years (Scoville & Norman 1988; Norman & Scoville 1988; Norman 1988).

These results are in good quantitative agreement with those of Hernquist (1989), in spite of the differences between the two computational approaches, as indicated in §4.3 above. One discrepancy is that our fiducial model suffers a slightly more intense radial gas inflow than the simulation described by Hernquist (1989), in which 35% of the disk gas was driven to the center of the primary. This difference can be attributed to Hernquist’s use of a more diffuse satellite companion which suffered correspondingly greater tidal stripping than the satellite used in our calculations. Thus, although we employ the same satellite-to-disk mass as Hernquist (1989), a slightly larger fraction of the companion’s mass survived intact, inducing a somewhat greater tidal response in the disk. Clearly, however, this difference is not relevant to the basic findings of either study, as a result in better agreement with Hernquist (1989) would presumably be obtained with our current models if a slightly less massive satellite were employed. (For a discussion, see Walker, Mihos & Hernquist 1994.)

5.2. Dynamics of the Response

Our present investigation goes well beyond those of Hernquist (1989) in the sense that we have considered the sensitivity of the effects to some variations in physical and numerical parameters.
For example, it appears that the onset of gas inflows is relatively insensitive to the temperature of the gas, provided that it is not extraordinarily high. The results are also not affected by feedback from the ensuing starburst (Mihos & Hernquist 1994c,d), at least when relatively simple prescriptions are used to include star formation in the gas (Mihos & Hernquist 1994e).

Using our fiducial model, we have established that the gas inflows are driven by gravitational torquing of the gas by the stellar disk, in response to the tidal forcing of the companion galaxy, in a manner noted by other workers in related studies (e.g. Combes, Dupraz & Gerin 1990; Barnes & Hernquist 1991; Barnes & Hernquist 1994). This outcome can plausibly be blamed on the different dynamics of the gas relative to the stars in response to the time-varying, non-axisymmetric potential which develops during the final stages of the merger. The disk gas will dissipate energy in shocks and radiate away excess internal energy unless it follows closed orbits; a requirement not shared by the stellar disk. As the potential changes most rapidly, it becomes increasingly difficult for the gas to avoid rapidly dissipating energy in strong shocks. The establishment of these shocks is such that the gas is torqued by the disk stars (Barnes & Hernquist 1991), removing angular momentum from the gas and driving it to the center of the disk. Regrettably, the uncontrolled nature of our experiments makes them poorly suited for examining the detailed orbital response of the various components at late times in the merger when conditions change most rapidly. Thus, while we believe that numerical effects are not responsible for the dynamics seen in the models, we have not demonstrated that, e.g. the artificial viscosity plays a negligible role in the nuclear inflows in our models. (Although we have performed simulations in which we varied the magnitude of the artificial viscosity by factors of several in each direction with inconsequential results.) It appears to us that a more fruitful approach to fully isolate all the dynamics would be to employ more controlled experiments in which disks are subjected to external, time-varying perturbations that can be applied systematically.

5.3. Structure of the Primary Galaxy

As evidenced by the simulations described in §4.2, the structure of the primary galaxy is critical in determining the nature of gas inflows that can be induced by accreted companions. A related discovery was made by Mihos & Hernquist (1994a), who found that the presence of compact bulges in galaxies involved in a major merger delayed the onset of gas inflows until late in the encounter, resulting in stronger and more abrupt starbursts than in collisions between pure disk-halo galaxies (e.g. Mihos et al. 1991, 1992). Our results imply that radial inflows in minor mergers can not only be delayed but be entirely suppressed by variations in the structure of the primary. At present, with our limited set of simulations, we are unable to isolate the precise mechanism responsible for this effect, although it may be related to previous claims that the presence or absence of an inner Lindblad resonance may play an important role in gas flows near the centers of disk galaxies (e.g. Combes 1988; Kenney et al. 1992). Our results suggest that
extremely violent nuclear starbursts may be limited to disk galaxies with small bulge to disk ratio. Observationally, the connection between central starbursts and bulge to disk ratio is still unclear; however, the wide variation of galaxy properties along the Hubble sequence (Roberts & Haynes 1994) would make any such connection difficult to isolate.

Our results on the sensitivity of the inflow to the presence of bulges differs from that of Barnes & Hernquist (1991, 1994), who found that dissipation in major mergers was not suppressed by the presence of bulges in the merging galaxies. However, while the bulges used in their galaxy models were comparable in mass to those employed here, their bulges were significantly more diffuse. Therefore, it is not bulge to disk ratio alone that drives the effects noted here, but rather the central density of the bulge component. Evidently bulges must have sufficient density in order to suppress radial inflows of gas during galaxy mergers.

5.4. Evolution Along the Hubble Sequence

By analogy with the merger hypothesis for the origin of elliptical galaxies (Toomre & Toomre 1972; Toomre 1977), Schweizer (1990) has proposed that at least some early-type spirals and S0’s might have resulted from the accretion of less-massive companions by late-type disk galaxies. While not designed specifically to examine this issue, our models generally support this notion. Although we do not address the ultimate fate of the central gas clump formed in these encounters, models which include star formation (Mihos & Hernquist 1994c) indicate that this gas is almost completely transformed into stars during an induced central starburst. Therefore, the remnants of these encounters may well resemble S0 galaxies, at least to the extent that they are much less gas rich than their progenitor disks, contain thickened disks, and exhibit only rather diffuse spiral structure. The latter property is also characteristic of amorphous galaxies (e.g. Sandage & Brucato 1979), suggesting that they may have formed in this manner. Perhaps of most relevance are S0 and early-type galaxies possessing central X-structures (e.g. Whitmore & Bell 1988). In the past, these features have often been explained by the accretion of material from a passing galaxy during a transient encounter (e.g. Hernquist & Quinn 1989), although stellar-dynamical models like those reported here have shown that such features can arise through minor mergers (Walker et al. 1994a). The present simulations demonstrate further how gas can be removed from the disk in such minor mergers, leaving behind remnants with diffuse gas content and morphologies similar to a number of well-studied S0 galaxies with X-structures (see, e.g. Walker et al. 1994b).

5.5. Relation to Active Galaxies

Of greatest interest is the possibility that minor mergers may be responsible for the onset of unusually energetic activity in the nuclei of some galaxies. Simulations like those described in §§3
and 4, but which include a simple prescription for star formation and feedback, show that mergers like our fiducial model can produce nuclear starbursts with characteristics reminiscent of those observed in some cases (Mihos & Hernquist 1994c,d). Clearly, our calculations are not relevant to those systems that likely consist of two merging galaxies that are comparable in mass, as appears to be the case for many of the ultraluminous sources (e.g. Sanders 1992). However, to the extent that minor mergers are a more common type of event, the simulations here may be relevant to a larger percentage of starbursts. One caveat, of course, is our finding that the presence of a compact bulge can effectively halt central inflows of gas induced by accretions, inhibiting nuclear starbursts. If this result is supported by future modeling, we must conclude that starburst activity triggered by minor mergers will be limited to only certain progenitors; namely, late-type disk galaxies that are rich in gas. Such cases are still of great interest, however, as it may well be the case that disks form before bulges and in view of the fact that galaxies may generally be assembled in a clumpy manner (e.g. Searle & Zinn 1978). In that event, we anticipate that minor mergers may have played a greater role in triggering nuclear activity in galaxies early in the Universe.

Our models also suggest that any induced central activity may not occur until the satellite sinks to the central few kiloparsecs of the primary center. During the early stages of the encounter, the gas inflow rates are relatively small; rather than driving central activity, the merger may excite heightened disk star formation (Larson & Tinsley 1978; Kennicutt et al. 1987). Models which include star formation (Mihos & Hernquist 1994d) indicate that the star formation rate at these early times remains mostly constant, increasing only as the nuclear inflow develops. Accordingly, studies which seek to link starburst or AGN activity with the presence of companion galaxies (e.g. Dahari 1984; Keel et al. 1985; MacKenty 1989) may actually underestimate the statistical connection, as galaxy samples selected by the presence of companions may exclude many late-stage active mergers where the companion is difficult to discern.

More speculatively, it has been suggested at various times that galaxy collisions may be related to the onset of various types of active galactic nuclei (for a review, see Barnes & Hernquist 1992b). Owing to the limited resolution of our simulations we are unable to address this interesting possibility. Nevertheless, there is circumstantial evidence which favors this interpretation. Many Seyfert galaxies, in particular, are amorphous or otherwise disturbed (MacKenty 1989, 1990), and are morphologically similar to the remnants formed by minor mergers with gas-rich disks. While it is clearly premature to blame all, or even some occurrences of Seyfert activity on minor mergers, we believe that further investigation of this issue is warranted, based on the results reported here.

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Fig. 1.— Evolution of gas in isolated disk/halo system. Time is noted in the upper right corner of each panel and individual frames measure 20 length units per edge.

Fig. 2.— Evolution of the stellar disk in fiducial satellite merger, seen face-on to the disk plane. In each panel, the cross locates the instantaneous position of the satellite, and time is noted in the upper right corner. The frames measure 20 length units per edge.

Fig. 3.— Same as Figure 2, but seen edge-on to the disk plane.

Fig. 4.— Same as Figure 2, but showing the gas response in the disk.

Fig. 5.— Evolution of the satellite galaxy in fiducial satellite merger, seen face-on to the disk plane. Time is noted in the upper right corner of each panel. The frames measure 20 length units per edge.

Fig. 6.— Detailed view of the evolution of the gas in fiducial satellite merger, seen face-on to the disk plane. Crosses in each panel indicate the location of the satellite, and time is noted in the upper right corner. The frames measure 2 length units per edge.

Fig. 7.— Cumulative distribution of gas mass in the fiducial satellite merger. Note that accretion of gas mass onto the central clump has effectively ceased by T=81.6.

Fig. 8.— Evolution of orbital (L), spin (S), and total (J) angular momentum of galaxy components in the fiducial satellite merger: a) halo, b) disk stars, c) gas clump, d) satellite core.

Fig. 9.— Evolution of the torques experienced by gas in nuclear accumulation. Panel (a): comparison between total torque and loss of spin angular momentum; panel (b): decomposition of total torque into gravitational and hydrodynamical components; panel (c) decomposition of gravitational torque by mass component. “Disk” refers to disk stars, “halo” to halo particles, “satellite” to satellite particles, and “gas” to the gas not driven into the central gas clump; panel (d): decomposition of torque from disk stars into contribution from different mass zones (see text).

Fig. 10.— Decomposition of stellar half-mass distribution into Fourier modes during the merger.

Fig. 11.— Evolution of the gas in satellite merger with $T_{\text{gas}} = 3 \times 10^{3}$ K, seen face-on to the disk plane. The cross locates the position of the satellite in each frame, and time is indicated in the upper right corner. Each panel measures 2 length units per edge.

Fig. 12.— Same as Figure 11, but for the simulation employing a $T_{\text{gas}} = 10^{5}$ K gas.

Fig. 13.— Final cumulative gas mass distribution for various gas temperatures.
Fig. 14.— Distribution of gas densities following the merger in models employing gases at different (isothermal) temperatures. From right to left, top to bottom, the frames show models with gas temperatures $T = 3 \times 10^3, 10^4, 3 \times 10^4, 10^5, \text{ and } 3 \times 10^5 \text{ K}$.

Fig. 15.— Evolution of the stellar disk in satellite merger with primary which includes a dense bulge, seen face–on to the disk plane. In each panel, the cross locates the instantaneous position of the satellite, and time is noted in the upper right corner. The frames measure 20 length units per edge.

Fig. 16.— Same as Figure 15, but showing the gas response in the disk.
Fig. 17.— Decomposition of stellar half-mass distribution into Fourier modes during the merger involving the primary containing a dense central bulge.

Fig. 18.— Detailed view of the evolution of the gas in satellite merger with primary which includes a dense bulge, seen face-on to the disk plane. Crosses in each panel indicate the location of the satellite, and time is noted in the upper right corner. The frames measure 2 length units per edge.

Fig. 19.— Final cumulative distribution of gas mass in the fiducial satellite merger (solid line) and runs which include dense bulges of mass 1/3 (dash-dotted line) and 1/9 (dotted line). For comparison, the initial gas mass distribution is also shown (dashed line).