THE ASTROPHYSICAL JOURNAL, 370:L65–L68, 1991 April 1

FUELING STARBURST GALAXIES WITH GAS-RICH MERGERS

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Received 1990 August 15; accepted 1991 January 2

ABSTRACT

We model the dynamics of gas in a merger of two disk/halo galaxies of equal mass using a hybrid N-body/gasdynamics code. Violent tidal forces acting on the disks draw out extended tails and trigger the formation of central bars. As such bars form, gas in the inner half of each disk loses most of its angular momentum through gravitational torques and falls into a compact cloud within the center of the galaxy. These nuclear gas clouds merge when their parent galaxies do, resulting in the rapid assembly of $\sim 5 \times 10^9$ $M_\odot$ of gas, which may plausibly be identified with the large central clouds seen in CO observations of galaxies such as NGC 520. Violent star formation in such central gas clouds, which seems inevitable, offers a likely explanation for luminous *IRAS* galaxies and may contribute significantly to the central stellar populations of merger remnants. If some of the nuclear gas can continue to lose angular momentum, it may be able to fuel or even form a central black hole, resulting in a radio galaxy or possibly even a quasar.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: interactions — galaxies: intergalactic medium — galaxies: internal motions — galaxies: nuclei — galaxies: structure

1. INTRODUCTION

A growing body of evidence suggests that some starbursts and active galaxies may be triggered by mergers. Integrated colors led Larson & Tinsley (1978) to conclude that many interacting and merging galaxies have undergone bursts of star formation involving up to $\sim 5\%$ of their total luminous mass with durations of $\lesssim 10^8$ yr. The *IRAS* survey revealed the existence of many galaxies with far-infrared luminosities exceeding 10^{11} $L_\odot$ (Soifer et al. 1984a, b); these objects generally exhibit shells, loops, tidal tails, complex velocity fields, and other features typical of recent merger remnants (Joseph & Wright 1985; Sanders et al. 1988a). Many bright radio galaxies also possess such structural peculiarities; these characteristics, combined with evidence for recent star formation and the absence of nearby companions, imply that some radio galaxies may have resulted from mergers of disk galaxies (Heckman et al. 1986; Baum & Heckman 1989; Vader, Heisler, & Frogel 1989). Similar morphological features have been seen in low-redshift quasars, though the characterization of these objects as merger remnants is less certain owing to their great distances (cf. Stockton 1990).

These observations support the idea that a merger or violent interaction might "bring *deep* into a galaxy a fairly *sudden* supply of fresh fuel in the form of interstellar material" (Toomre & Toomre 1972, *their* italics). A detailed understanding of the physics of such an influx has remained elusive. To produce the massive nuclear concentrations of molecular material detected in recent CO interferometer observations of galaxies such as Arp 220 (Scoville et al. 1986) and NGC 520 (Sanders et al. 1988b), much of the interstellar gas initially distributed throughout a galaxy must collect in a central cloud with dimensions of $\sim 10^2$ pc. Moroever, the rapid star formation seen in these systems implies that such nuclear gas clouds must assemble in $\lesssim 10^8$ yr (Larson 1987). Evidently it is necessary that the "violent mechanical agitation" attending the merger of two comparable disk galaxies somehow conspires to reduce the angular momentum of the gas by one to two orders of magnitude on a dynamical time scale.

To study the mechanisms which transport angular momentum in the gas, we have run models of merging galaxies using a self-consistent N-body plus gasdynamics code. We find that under some conditions gravitational torques can rob the gas of angular momentum rapidly enough to fuel the nuclear starbursts which seem to be associated with mergers. Not the least because effects related to star formation and supernovae have not been included, our results are intended to be illustrative rather than comprehensive. In the following section we present a simulated merger between two gas-rich disk galaxies of equal mass, and in the last section we discuss some implications of such experiments.

2. A MERGER WITH GAS

Figure 1 (Plate L4) shows the dynamical evolution of the gas in a pair of merging disk galaxies, simulated with the self-consistent three-dimensional code described in detail by Hernquist & Katz (1989). In brief, we use a tree algorithm (e.g., Barnes & Hut 1986; Hernquist 1987) to compute gravitational forces on both gaseous and collisionless components, and smoothed particle hydrodynamics (Lucy 1977; Gingold & Monaghan 1977) to model the behavior of the gas. This approach treats the interstellar gas of the galaxies as a reasonably smooth but highly compressible fluid; the strong shocks occurring in galactic collisions are handled using artificial viscosity. We include radiative cooling down to $\sim 10^4$ K, where we place a floor on the cooling curve as discussed by Hernquist (1989a, b). At the densities involved, cooling is very rapid and the bulk of the gas hovers near the cutoff temperature.

The model galaxies used in this calculation are similar to those employed by Barnes (1988); each consists of a compact central bulge, a thin exponential disk, and an extended spheroidal halo, with mass ratios of 1:3:16, respectively. The gas, amounting to 10% of the disk mass, is initially distributed just like the disk stars. Each galaxy contains a total of 45,056 particles; 8192 for the gas, the rest representing the collisionless

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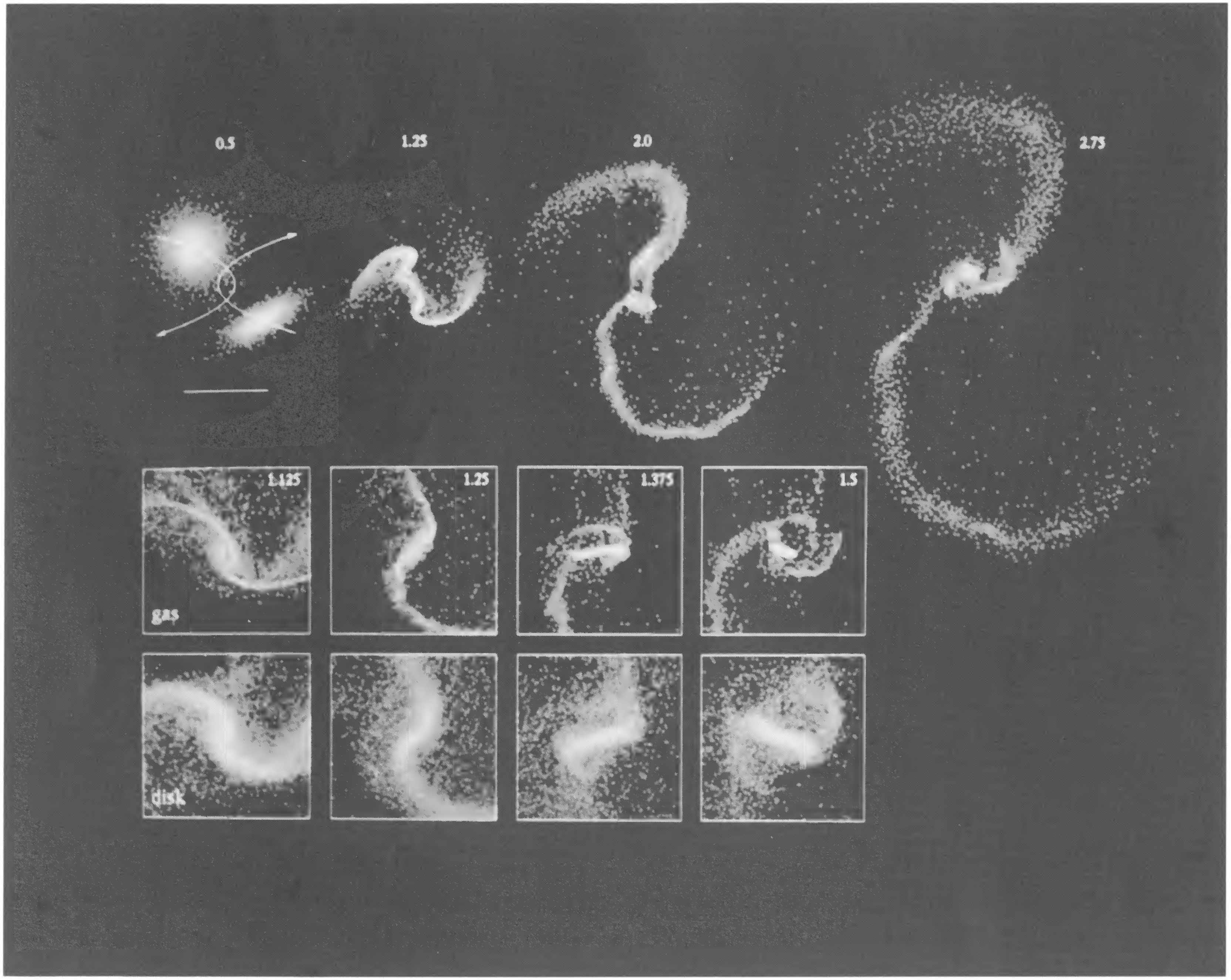

Fig. 1.—A close parabolic collision and merger of two gas-rich disk/halo galaxies, simulated using a combined N-body/SPH code and projected onto the orbital plane. The large, unframed plots show the evolution of the gas distribution as the two galaxies approach each other, interact, and merge. The two rows of small plots are $5\times$ enlargements showing the evolution of the gas (*top*) and disk stars (*bottom*) in the face-on disk. Numbers give elapsed times since the start of the simulation, with pericenter occurring at $t = 1$; the solid bar under the first plot is one unit long.

Barnes & Hernquist (see 370, L65)

components. We report our results in an arbitrary system of units with $G \equiv 1$. The total mass of each galaxy is 1.25, its binding energy is -1.38, and the net half-mass radius is 0.25. The disks have exponential scale lengths of $\alpha^{-1} = 1/12$ and rotate once every 0.93 time units at a radius of $3\alpha^{-1}$. Our units of length, mass, and time correspond roughly to 40 kpc, $2.2 \times 10^{11}\ M_{\odot}$, and 250 Myr, respectively.

The two galaxies were released on parabolic trajectories which, if extrapolated, would reach a pericentric separation of $R_p = 0.2$ (or $2.4\alpha^{-1}$) at time $t = 1$. Such a close encounter leads to violent tidal distortions, exacerbated by the prograde orientations of both disks. In the second view, only 0.25 time units after pericenter, the face-on disk has been deformed into a extremely open spiral, while its inclined ($i = 71°$) companion has launched a major tidal tail extending to the left. These features, although most crisply defined by the gas, are closely followed by the other disk material. But by the third view, roughly one rotation period after pericenter, the gas and stellar distributions have developed significant differences. Most conspicuous at this scale are the dense knots in the lower tidal tail, and the fact that the gas flowing along the bridge from the lower galaxy to the upper does not significantly interpenetrate the latter. The last view shows the two galaxies on the point of merging; on this scale, the gas is still far from relaxed. Nonetheless, a large fraction of the gas—over half—has already collapsed into a central cloud too small to resolve in this figure.

The small plots below the main series illustrate some of the dynamics responsible for this remarkable central accumulation of gas. Shown 5 times enlarged are the gas (*upper row*) and stars (*lower row*) from the center of the face-on, prograde disk. These four frames span a relatively short time interval; from slightly after pericenter to only one-half a rotation period after. In this interval, the violently perturbed stellar component forms a strong bar, much as reported in previous studies (e.g., Noguchi 1987). The gas develops a similar distribution, but strong shocks appear even in the first of these small frames. By the third small frame, the gas bar has become significantly shorter and narrower than the stellar bar and leads the latter by an angle of $\sim 5°$. As a result, angular momentum is rapidly transported from the gas to the stars, and the last of these small frames finds $\sim 50\%$ of the gas originally distributed throughout the galactic disk in a small oval ring at the center. In contrast, a control experiment with an isolated galaxy found essentially no central accumulation of gas over a comparable interval.

To examine the mechanism which drives the gas to the center of this disk, we computed the specific torque τ acting on the Lagrangian volume of gas which lies within a radius of 0.025 at time 1.75. In Figure 2 we plot the gravitational (*circles*) and hydrodynamic (*stars*) torques on the gas as functions of time. The gas begins to lose angular momentum shortly before pericenter, and by $t = 1.75$ its angular momentum has fallen to a mere $\sim 4\%$ of the original value. This is entirely a result of gravitational forces which couple the gas to the collisionless matter; gasdynamic torques are measurable only briefly around the moment of pericenter and, in fact, act in the opposite sense to the gravitational torques.

A more detailed analysis shows that *before* pericenter most of the torque is due to the gravitational field of the other galaxy. Such transfers of spin angular momentum to orbital motion in slow prograde passages were anticipated by Toomre & Toomre (1972) and studied in detail by Palmer & Papaloizou (1982). *After* pericenter, on the other hand, the torque on

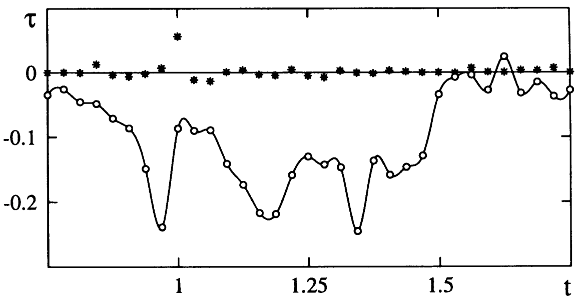

FIG. 2.—Specific torques acting on the Lagrangian volume of gas which collects at the center of the face-on disk. Open circles connected by a smooth line show gravitational torques exerted on the gas by the rest of the system, while stars show torques due to hydrodynamic forces.

the gas is largely due to the stellar bar shown in the bottom row of frames in Figure 1. This torque arises because the stellar bar tends to lag behind the gas bar by a few degrees; as a result, the gas loses angular momentum and collects at the center of the galaxy. An effect of this kind has often been reported in models of time-dependent gas flows in barred spiral galaxies (e.g., Simkin, Su, & Schwarz 1980; Schwarz 1984; Noguchi 1988). As the latter author carefully points out, it is not clear from the published models if the presence of an inner Lindblad resonance is crucial for rapid inflow of gas. In the present model the pattern speed of the bar lies just above the peak value of $\Omega - \kappa/2$; moreover, the *only* orbit family occupied by the gas is the parallel family X_1 (van Albada & Sanders 1982). Our results support the suggestion that an ILR is not necessary for rapid gas inflow.

On reflection, it is not very surprising that gas collects at the center of the disk. Strong radiative shocks are expected and clearly present in the gas flow. At each shock front the gas loses energy, or more properly in a rotating frame of reference, Jacobi constant. The gas orbits, while remaining within the family X_1, drop ever deeper into the potential well, becoming either narrower, in the direction transverse to the bar, or shorter, in the direction parallel to it. Both trends are indeed visible in Figure 1; the gas bar initially becomes narrower, but once it gets very thin the only way it can continue liberating the energy radiated away is to become shorter. A similar situation arises in accretion disks with tidally driven spiral shock waves (e.g., Spruit 1990), where the angular momentum of the gas is transferred to the companion responsible for the tidal field. Here, the angular momentum of the gas is transferred to the stellar bar, which plays a role analogous to that of the companion.

Concerned that numerical effects might compromise our results, we ran additional experiments varying the artificial viscosity by a factor of 3 in each direction and even changing its functional form. These variations had no significant effect on the amount of gas flowing to the center, nor did reducing the particle number by a factor of 2. On the other hand, the central inflow was completely shut off when we disabled radiative cooling. With cooling turned off, the gas in the inner disks was shocked to $\sim 10^6$ K shortly after the encounter and formed an extended cloud surrounding the center of each galaxy. To flow to the center, the gas must evidently not only shock but also *radiate*.

The other disk in this calculation, although inclined by an angle of 71° to the orbital plane, likewise develops a strong bar after the encounter. The gasdynamics in this disk are more complicated since a significant amount of material flows along the bridge connecting the galaxies and finds its way to the central regions. On the whole, however, the effects of the encounter are much the same as for the face-on disk; within one rotation period after the passage, a large amount of gas collects at the center of the inclined disk also.

The merger of these galaxies culminates with the collision of the two central gas clouds. Some cancellation of angular momentum occurs since these clouds spin about different axes. By time $t = 3$, only a couple of rotation periods after the two galaxies first met, $\sim 60\%$ of *all* their gas is contained within a radius of 0.005, as shown in the right-hand part of Figure 3. This corresponds roughly to a mass of $5 \times 10^9 M_\odot$ within a radius of only 200 pc. One must bear in mind that the dynamics at such small scales is strongly influenced by the gravitational softening used in this calculation. We use spline kernel softening (Hernquist & Katz 1989) with $\epsilon = 0.015$; for separations $r > 2\epsilon$ the potential is exactly $1/r$. It seems unlikely that this softening could lead us to overestimate the amount of gas which collects at the center of the merger remnant. On the other hand, the gas could be depleted and possibly dispersed by star formation before reaching the high central concentration seen here.

In marked contrast to the gas distribution, the central *stellar* component is smooth and regular, as shown on the left-hand side of Figure 3. Like a number of other studies (e.g., Barnes 1988), we find the stellar distribution follows a de Vaucouleurs law. The projected radius containing half the total luminosity is 0.1 length units, corresponding to ~ 4 kpc. It may seem remarkable that such a smooth distribution is set up so soon after the merger. However, near-IR observations of Arp 220 indicate that it too has already approached a similar profile (Wright et al. 1990) even though two nuclei separated by $\gtrsim 300$ pc are still visible (Norris 1988; Graham et al. 1990).

3. DISCUSSION

The model shown here illustrates one way in which tidal effects promote rapid nuclear gas inflows in strongly interacting and merging galaxies. Tidal forces during a close encounter can trigger the formation of a bar in a normally stable disk. The dissipative gas tends to lead the stellar bar in phase, resulting in an efficient transfer of angular momentum by gravitational torques. In the example shown here, half of the gas settles into an oval ring within the inner kiloparsec of each disk. When the two galaxies finally merge, these gas rings coalesce, resulting in a central gas cloud that by the end of the simulation comprises more than half of the gaseous material.

Our results are most closely related to those of Negroponte & White (1983) who used a discrete-cloud approximation to represent the gas in mergers of disk galaxies of equal mass. They also found that significant quantities of gas settle into the core of the remnant. Owing to the more limited dynamic range of their calculations, Negroponte & White could not determine the detailed mechanisms responsible for nuclear inflow of gas in their models. However, the amount of gas in the inner regions of their remnants is in good quantitative agreement with that found here, suggesting that the basic conclusions common to their calculation and ours are not unduly sensitive to details of the models. In this regard, note that the gas in our models remains largely isothermal, with a temperature of $\sim 10^4$ K, and therefore dissipates energy at roughly the same rate as a collection of discrete clouds with a velocity dispersion of ~ 10 km s^{-1}, typical for molecular clouds in our own Galaxy.

More recently, Noguchi (1988) has studied transient encounters between disks of stars and gas and a point perturber of comparable mass. He too found that direct parabolic collisions can trigger bar formation in stable self-gravitating disks, leading to a nuclear inflow. The mechanism which removed the angular momentum of the gas in his models was not clear, although the evolution shown in his Figure 1 is very similar to that presented in the corresponding figure here. However, Noguchi modeled the dark halos around his galaxies as rigid potential wells and thus could not properly treat the orbital decay which would have occurred in a more realistic simulation. We suspect that most encounters sufficiently violent to induce rapid nuclear inflows in typical disk galaxies lead to mergers on a relatively short time scale.

If this suspicion is correct, then many disk galaxies with nuclear starbursts or other activity may have instead accreted much less companions which are much less massive. Models developed by Hernquist (1989a, b) show that the accretion of low-mass companions by disks can also lead to nuclear inflow of gas. In those simulations the galactic rotation curve and tidal impulse were such that the stellar disk did not form a bar. Nevertheless, local compression of the gas by the tidal field of the companion and dissipation of kinetic energy in shocks led to fragmentation of the gas under the influence of its own self-gravity. Loss of angular momentum by the gas fragments

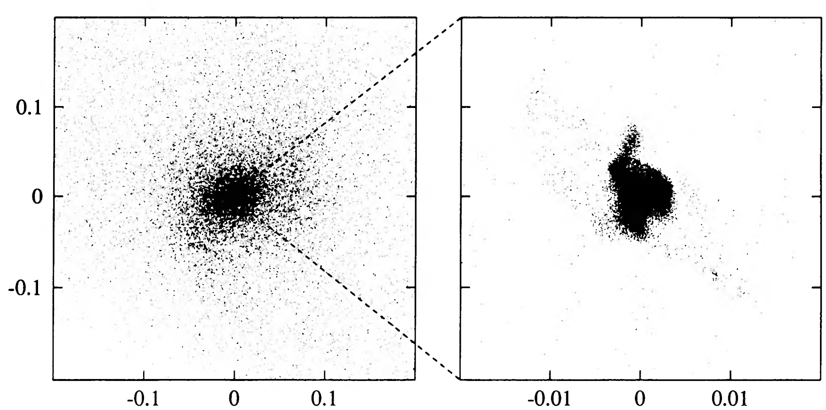

FIG. 3.—*Left:* stellar distribution of the merger remnant at time $t = 3$, viewed face-on to the orbital plane. Only half the particles are plotted to reduce crowding. *Right:* $10\times$ enlargement of the central region, showing the distribution of the gas particles. The central gas cloud contains some 60% of the gas in the system.

to the disk stars through dynamical friction resulted in rapid nuclear inflow. Additional unpublished simulations show that bar-driven inflows can also occur when disks accrete low-mass companions if the disks in isolation are nearly bar-unstable, as judged by the Ostriker-Peebles criterion (Ostriker & Peebles 1973).

The fate of the nuclear gas clouds produced in these models is problematical since star formation and supernova heating have been ignored in the simulations. Given the high densities, an episode of rapid star formation seems likely, and observations of nuclear gas clouds in starburst systems such as NGC 520 (Sanders et al. 1988b) support this conjecture. In the short term, these starbursts may power outflows or "superwinds" (e.g., Heckman, Armus, & Miley 1990). After the fireworks are over, these merger remnants may be left with a central stellar population formed from the nuclear gas. Dissipation permits the gas to attain much higher phase space densities than allowed in purely stellar-dynamical mergers, in accord with some of the known differences between ellipticals and spirals (Carlberg 1986; Kormendy 1989; Vedel & Sommer-Larsen 1990). Star formation could also generate or enhance metallicity gradients in the remnant. Since the gas in the core of the remnant loses such a large fraction of its intrinsic angular momentum, it retains little imprint of its initial rotation and is largely decoupled from the rest of the galaxy. Depending on the history of star formation, the gas may form a kinematically distinct core similar to those observed in many normal ellipticals (Franx & Illingworth 1988).

Finally, the nuclear gas flows seen in these models may be able to fuel an active galactic nucleus. As Gunn (1979) stressed, processes which extract angular momentum from the gas are critical to the onset of nuclear activity in galaxies. A further reduction of 10^4 in angular momentum would be required before the gas cloud produced in our simulation could be accreted by a $10^8\ M_\odot$ black hole; our models lack sufficient dynamic range to determine whether or not the gas will continue to shed angular momentum. However, a variety of physical arguments suggest that once the gas is self-gravitating, fragmentation and instability can lead to further radial inflow (e.g., Begelman, Blandford, & Rees 1984; Lin, Pringle, & Rees 1988; Norman & Scoville 1988; Scoville & Norman 1988; Shlosman, Frank, & Begelman 1989). If so, the morphological similarities between this model and objects such as Arp 220 are not coincidental, and the infrared luminosity of the latter may derive in part from dust-enshrouded quasars (e.g., Sanders et al. 1988a, but see Rieke 1988). However, it is by no means clear that such "buried quasars" can burn off the surrounding clouds without also dispersing their fuel supplies. If sufficient fuel remains, perhaps confined to a dense molecular torus (Krolik & Begelman 1988), then mergers may account for some of the quasars and other active galaxies seen at high redshifts (e.g., Roos 1985). On the other hand, a rapidly rotating black hole, even if starved once the clouds disperse, may still power a high-luminosity radio source like those seen in "young" radio galaxies (Baum & Heckman 1989; Vader et al. 1989). Further observational and theoretical studies are required to decide if the peculiar kinematics and colors of such objects are consistent with recent mergers of disk galaxies.

We thank Mitch Begelman, Jim Gunn, Richard Larson, Colin Norman, Nick Scoville, Alar Toomre, and Scott Tremaine for discussion about active galactic nuclei and dynamics of gas in galaxies. This work was supported in part by a generous allocation of Cray Y-MP time from the Pittsburgh Supercomputing Center. L. E. H. was supported in part by Calspace grant CS 71-90.

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