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The AGN-Disk Dynamics Connection

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Abstract

Any connection between central activity and the large-scale dynamics of disk galaxies requires an efficient mechanism to remove angular momentum from the orbiting material. The only viable means of achieving inflow from kiloparsec scales is through gravitational stresses created by bars and/or mergers. The inflow of gas in bars today appears to stall at a radius of few hundred parsec, however, forming a nuclear ring. Here we suggest that bars in the early Universe may have avoided this problem, and propose that the progenitors of central supermassive black holes (SMBHs) are created by gas that is driven deep into the centers of galaxies by bars in the early stages of disk formation. The coincidence of the QSO epoch with galaxy formation, the short lifetimes of QSOs, and the existence of SMBHs in the centers of most bright galaxies are all naturally accounted for by disk dynamics in this model. The progenitor SMBHs are the seeds for brighter QSO flares during galaxy mergers. We present a new study of bar weakening by central mass concentrations, which shows that bars are less easily destroyed than previously thought. An extremely massive and compact central mass can, however, dissolve the bar, which creates a pseudo-bulge component in the center of the disk.

1.1 Introduction

It now seems that the masses of supermassive black holes (SMBHs) in the centers of galaxies are strongly correlated with the larger scale dynamical properties of their host galaxies (Kormendy & Richstone 1995; Gebhardt et al. 2000; Ferrarese & Merritt 2000). Yet an utterly insignificant fraction of the mass of a galaxy had low enough angular momentum to create, or accrete directly onto, a SMBH in its center. Why the mass of the SMBH should be so closely related to the properties of its host galaxy is still an open question.

Material orbiting at a galacto-centric radius of a few kiloparsecs, where most of the baryonic galaxy mass resides, must have its angular momentum reduced by several orders of magnitude before it becomes of any relevance to nuclear phenomena. Thus, any connection between galaxy dynamics and nuclear activity requires a mechanism to remove enough angular momentum from the gas to enable it to accrete onto the SMBH. Viscous processes are too slow for gas to sink from orbits at large radii to small, even when augmented by magnetohydrodynamic instabilities (Sellwood & Balbus 1999), and significant radial migration requires gravitational torques. Spiral waves are weak, and generally do more churning of the gas than radial transportation (Sellwood & Binney 2002). Attention has therefore focused on the gravitational influence of the strongest non-axisymmetric features: bars in isolated systems and tides during mergers.

Since bars in galaxies today can reduce the angular momentum of gas in the disk by little more than one order of magnitude, other processes would be needed to drive gas originating in the main disk of the galaxy close enough to the nucleus to accrete onto it (see, e.g., Wada 2004). However, the removal of angular momentum by bars could have been somewhat more efficient as galaxies first formed, and we propose a possible connection between disk dynamics and early QSO activity.

It has often been noted that bright galaxies were assembled at about the same time that QSOs flare (e.g., Rees 1997), suggesting a causal connection. In fact, the luminosity function of X-ray selected AGNs seems to track the star formation history of the Universe remarkably closely (Franceschini et al. 1999). Since QSOs are believed to reside in the centers of galaxies (e.g., Bahcall et al. 1997; McLure et al. 1999), it is natural to suppose that they formed there. Many bright galaxies in the local Universe appear to host quiescent SMBHs which are assumed to be the fuel-starved engines of earlier QSO activity (Yu & Tremaine 2002; Ferrarese 2002).

Thus, a convincing model for the formation and evolution central SMBHs should offer answers to at least the following questions:

- Why should QSOs flare during an early stage of galaxy formation?
- Why are the centers of galaxies the preferred sites for QSOs?
- What interrupts the fuel supply to limit QSO lifetimes?
- Why is the mass of the central SMBH related to properties of the host bulge?

Here we outline a model that offers dynamical answers to the first three of these questions, but does not yet answer the fourth. The main ideas are: (1) most large galaxies developed a bar at an early stage of their formation, (2) the central engine is created from gas driven to the center by the bar, and (3) changes to the galaxy potential, caused by mass inflow itself, shut off the fuel supply to the central engine when the mass concentration reaches a small fraction of the galaxy mass. Furthermore, the central mass weakens the bar; we show that complete destruction of the bar creates a (pseudo-)bulge in the stellar distribution but, as yet, we are unable to demonstrate that this is a necessary consequence of SMBH formation. This picture was proposed by Sellwood & Moore (1999); Kormendy, Bender, & Bower (2002) argue for a similar idea with a somewhat different emphasis.

The early sections of this paper review the various ingredients that go into this picture, while the later sections put it together.

1.2 Gas Flow in a Simple Bar

Prendergast (1962) was among the first to realize that a rotating bar in a galaxy would drive large-scale shocks in the interstellar medium, which he identified with the straight, offset dust lanes commonly seen on the leading side of the principal axis of the stellar bar. His insight has been amply confirmed in a host of gas-dynamical calculations reported over the past 40 years.

The gas flow pattern is asymmetric about the axis of the bar, leading to a net torque between the bar and gas. The gas loses angular momentum (to the bar) and energy (in the shocks), which drives it inward. Unfortunately, the inflow rate is not easily predicted from theory or simulations because it depends not only on the mass model for the galaxy and bar, pattern speed, etc., but is particularly sensitive to the effective viscosity (i.e., numerical method and parameters and perhaps also the assumed equation of state). The reason is that the shock is offset farther from the bar major axis as the effective viscosity increases, leading to an increased rate at which the gas loses angular momentum.

It is generally desirable to neglect self-gravity in calculations of the gas flow pattern in a non-axisymmetric potential arising from the more massive stellar component. Self-gravitating, dissipative gas tends to form massive clumps that are, in reality, disrupted by energetic "feedback" from star formation. The wide range of spatial scales makes it impossible for a global simulation of the gas flow to include the small-scale gas dynamics of star formation and feedback in any meaningful way—processes that anyway are not fully understood. Thus, the simulator must include a number of *ad hoc* rules to add energy back to the gas, in addition to calculating its self-gravity, thus making the calculation enormously more expensive in computer time for a questionable improvement in realism.

Self-gravity in the gas should not, of course, be neglected when the gas component is more massive, or when the stellar component is not far from axially symmetric, so that the self-gravity of the gas *creates* the non-axisymmetric structure (e.g., Wada 2004). But this is not the regime of bar flow.

The standard work is by Athanassoula (1992), who shows that the gas builds up in a ring at the inner Lindblad resonance (ILR), if one is present, but is driven in still closer to the center if there is no ILR and the bar is strong. Whether an ILR exists depends on the degree of central concentration in the galactic mass distribution—generally a quite modest bulge component is likely to ensure that an ILR exists.

The conventional definition of the Lindblad resonance is for nearly circular orbits in an axisymmetric potential. The concept can readily be generalized for barred potentials to the region where the orientation of periodic orbits switches from parallel to perpendicular to the bar major axis, which occurs at a radius somewhat interior to that of the naïve definition of the ILR (e.g., Contopoulos & Grosbøl 1989). (The perpendicular orbit family may even disappear in weak bars with little bulge; gas flow without shocks or inflow is possible in such cases.) For simplicity, I loosely use the phrase "ILR ring" to describe the dense ring that forms in the region where gas settles onto non-intersecting orbits in the vicinity of the perpendicular orbit family.

1.3 Nuclear Rings

The general picture of gas inflow down a bar until it stalls at a ring is supported by observation: a gas-rich nuclear ring is seen in many barred galaxies, where an enhanced rate of star formation is observed. Beautiful examples are seen in *Hubble Space Telescope (HST)* images: e.g., NGC 4314 (Benedict et al. 1998) or NGC 1512 and NGC 5248 (Maoz et al. 2001). See also the paper by Carollo (2004).

Furthermore, mm interferometers are mapping the CO emission from the nuclear regions of nearby galaxies at unprecedented resolution (e.g., Sakamoto et al. 1999; Regan et al. 2001; Schinnerer et al. 2002; Sofue et al. 2003). The survey by Regan et al. includes some nice examples of gas accumulating in the centers of barred galaxies and even a partial ring with a central hole can be seen in NGC 4258, although the central hole is not detected in M100. A number of caveats about these data should be noted, however: (1) variations in excitation and optical depth of the CO lines would mean that the observed intensity does not perfectly reflect the CO distribution, (2) estimates of the total gas density depend on the adopted ratio of H_2 to CO, and (3) interferometers frequently detect only a fraction of the CO flux detected by single dishes; this is because they are sensitive only to the inhomogeneous component and are "blind" to smoothly distributed emission.

The very existence of star-forming gas rings requires that any inflow interior to the ring drains the ring more slowly than gas arrives from large radii. Wada (2004) reviews possible mechanisms that can drive inflow inside the ILR ring. We would add that Englmaier & Shlosman (2000) suggest that further mild inflow of gas inside the ILR ring could be achieved through globally driven sound (or pressure) waves. This suggestion is not supported by the *HST* images, however, which often reveal a multi-arm dust distribution that must be caused by other mechanisms. It is likely that spiral features are created by self-gravity in the star-gas mixture and that the behavior inside the ILR, where the quadrupole field of the bar is weak, may not be so different from that in the nuclear regions of unbarred galaxies.

1.4 Double Bars

While not directly relevant to the main theme of this paper, the recent discovery of double bars deserves a mention. These are too striking, and the isophotal twists are too great, to be simply the manifestation of a triaxial ellipsoidal light distribution viewed in projection. Erwin & Sparke (2002) find them to be "surprisingly common"; they are seen in at least 25% (perhaps 40%) of early-type barred galaxies. The random distribution of angles between the inner and outer (or main) bars strongly suggests separately rotating components.

The inner bar probably lies within the ILR of the primary and is some 10% to 15% of length of the primary bar. The origin and dynamics of double bars is not well understood at present, however (see, e.g., Maciejewski & Sparke 2000; Heller, Shlosman, & Englmaier 2001).

It is known that the gas flow pattern is *not* simply a scaled-down version of that in the principal bar; there are no offset dust lanes (Regan & Mulchaey 1999; Shlosman & Heller 2002) and inflow may even be inhibited (e.g., Maciejewski et al. 2002).

1.5 Do Bars Feed AGNs?

Most studies (e.g., Ho, Filippenko, & Sargent 1997) find no significant excess of AGN activity in galaxies with bars over their unbarred counterparts, although enhanced star formation in the circumnuclear environment has long been established (Hawarden et al. 1986). Erwin & Sparke (2002) also find no evidence for excess activity in double barred galaxies.

However, Laine et al. (2002) claim weak evidence ($\sim 2.5\sigma$) for an excess of Seyfert activity in barred galaxies, particularly of later Hubble types. We do not find their result compelling, because it is based on binary binning; there is a continuum both of bar strengths, and of Seyfert activity levels, and the fractions in each bin (Seyfert or non-Seyfert, and barred or not) must depend on where the dividing lines are drawn. Furthermore, visual classification of barred versus unbarred is subjective. It would be better to look for a correlation between a quantitative estimate of bar strength (e.g., Abraham & Merrifield 2000; Buta & Block 2001) and some index of "AGN activity."

1.6 Dissolution of Bars

Many studies (e.g., Pfenniger & Norman 1990) claim that central mass concentrations (CMCs) will dissolve bars. But there have been no previous systematic studies to determine what would be required to dissolve bars, either partially or completely; some (e.g., Friedli 1994; Hozumi & Hernquist 1999) have even claimed that very small CMCs will dissolve bars on a moderate time scale.

Yet bars with CMCs are common, a fact that has led to speculation that the observed bar fraction may indicate the "duty cycle" of bars in galaxies that repeatedly dissolve and form again (e.g., Bournaud & Combes 2002). Since just one cycle of bar formation and destruction leads to a dynamically very hot disk, such a scenario demands prodigious infall of fresh gas before a disk could become responsive enough to form a new bar. If bars really were fragile, this daunting requirement might need to be invoked, but, fortunately, we now know that real bars can survive with realistic CMCs.

We have made the first systematic study of the effect of a CMC on the survival of the bar and our two major findings are illustrated in Figures 1.1 and 1.2. We use the amplitude of the $m = 2$ Fourier component of the particle distribution, relative to the axisymmetric term, as a measure the bar amplitude. (See Shen & Sellwood 2004 for more details.)

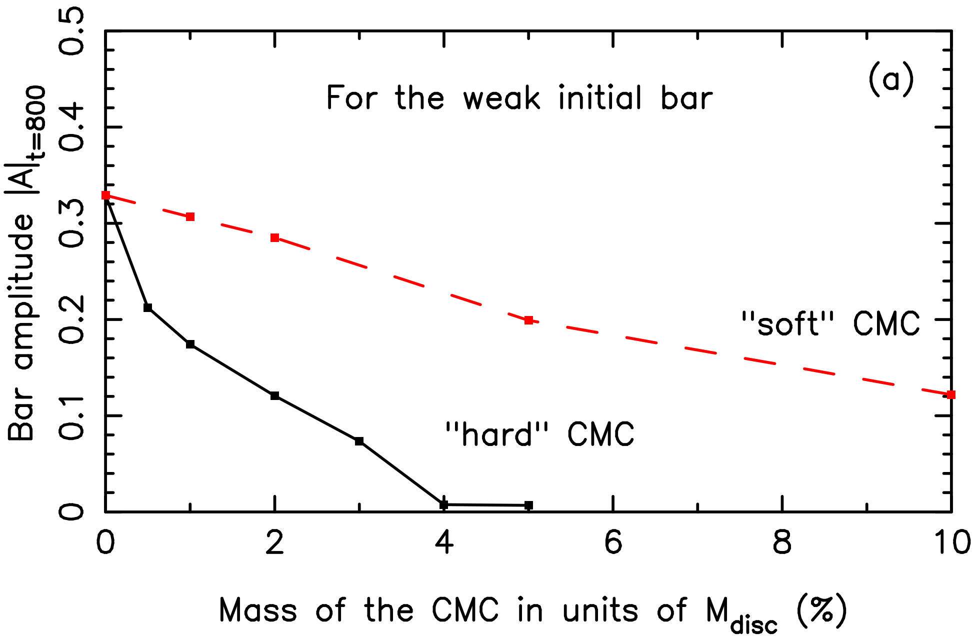
Figure 1.1 shows that bars are more robust than some previous studies have suggested. The bar is totally destroyed only when the CMC is very dense with a mass $\gtrsim 4\%$ of the *disk*—a less massive or more diffuse central mass weakens the bar, but does not totally destroy it within ~ 6 Gyr. Figure 1.2 shows the trend in bar amplitude at late times as the radial scale of the Plummer sphere used to model a CMC of fixed mass is varied. Dense CMCs are much more destructive than are diffuse CMCs, with a suggestion that the trend asymptotes to a limit as the size shrinks toward a point mass.

The critical value of $\sim 4\%$ of the *disk* mass needed for rapid bar dissolution by a pointlike CMC is enormously larger than the observed masses of central SMBHs. Gas accumulation at an ILR ring, for example, would also have to be quite unreasonably massive ($\gtrsim 10\%$ of the disk mass) to threaten the survival of a bar. Thus, neither current central SMBHs nor gas concentrations pose a significant threat to the survival of bars today.

Our results are based on very high quality *N*-body simulations, which have been extensively checked. The results shown are for a regime well clear of significant dependence on the numerical parameters. We have found it essential to pay particular attention to the time step. Figure 1.3 shows that poor orbit integration can cause an erroneous decay of the bar when too long a time step is used in the vicinity of a CMC. We integrate the orbits of particles in the vicinity of the CMC with time steps that are repeatedly halved (as many as nine or ten times) in a set of nested guard annuli around the CMC. It is likely that previous work overestimated the bar decay caused by CMCs because of inadequate care in orbit integration.

Not only does the substantial bar fraction in real galaxies suggest that CMCs pose little threat to bars, but the theoretical picture of scattering of stars on box orbits by SMBHs (e.g., Gerhard & Binney 1985) really does not apply to bars with rapidly tumbling figures where most orbits are loop-type (x_1) that avoid the center. A more likely mechanism for the destruction of bars by massive, dense CMCs is through the breakdown of regular orbits (e.g., Norman, Sellwood, & Hasan 1996). It is perhaps not too surprising that a large, dense mass is required to create a sufficiently extensive chaotic region.

It is very hard to imagine that bar destruction by this mechanism could be achieved more



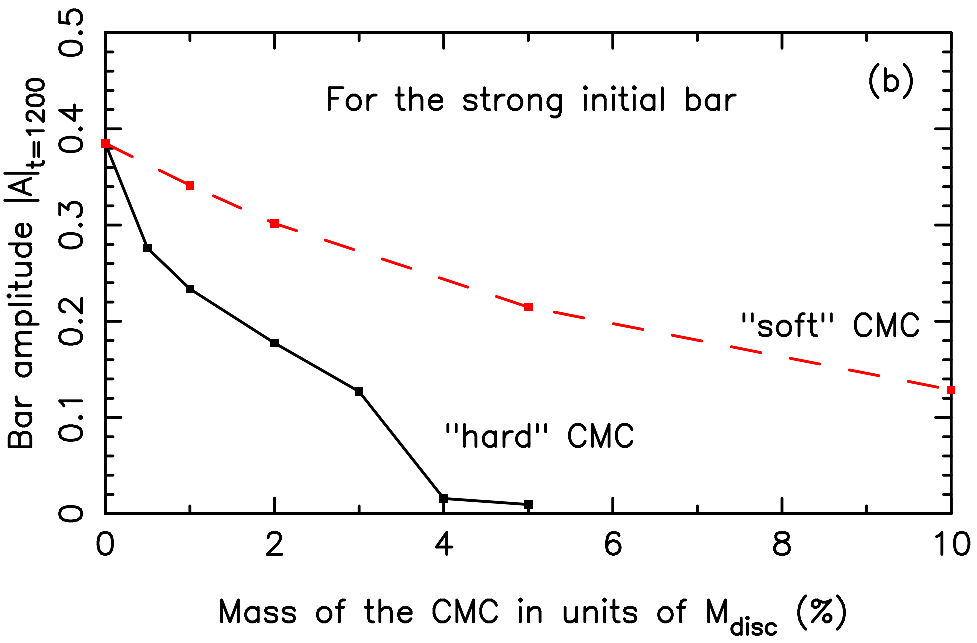


Fig. 1.1. The amplitude of the bar at a fixed time ($\sim$ 6 Gyr) after the introduction of CMCs having a range of masses, for both weak (*a*) and strong (*b*) initial bars. The bar is completely destroyed only by massive, dense CMCs.

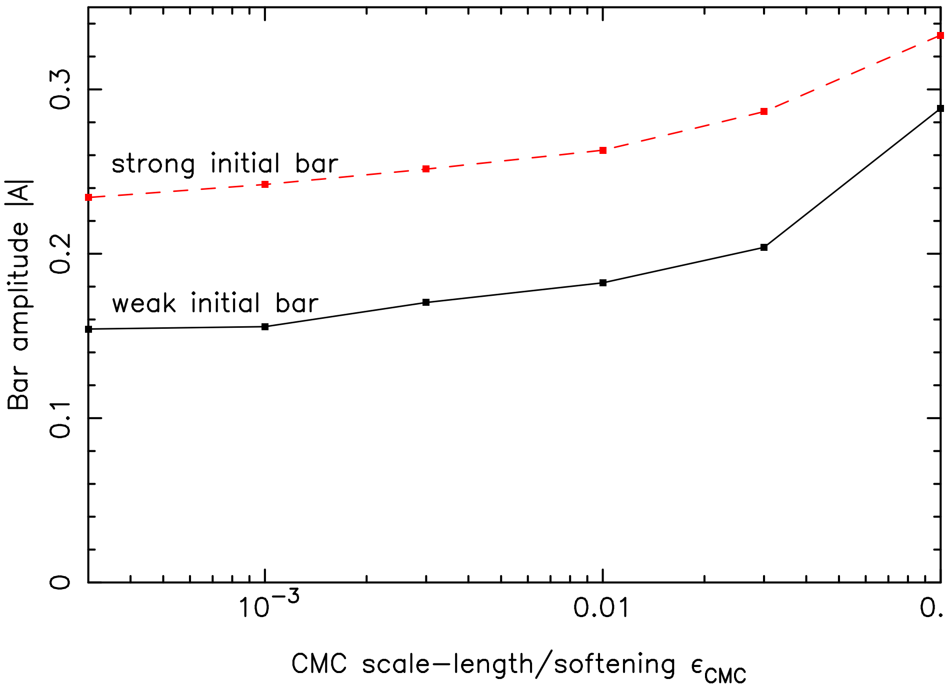


Fig. 1.2. The amplitude of the bar at a fixed time ($\sim$ 3 Gyr) after the introduction of CMCs having a range of central concentrations, for both strong and weak initial bars. The softening length ϵ_{CMC} is in units of the exponential scale length of the original disk. Bars are weakened more by dense CMCs than by diffuse ones.

than once in any given galaxy. The formation of a new bar is more difficult, because the disk has become both hot and has acquired a dense center (which inhibits one of the two possible bar forming mechanisms—see next section), but is thought to be possible. However, the dense center would cause the inflow in the new bar to stall at the ILR, preventing the growth of a compact CMC that could threaten its survival.

1.7 Formation of Bars—a Tale of Two Halos

There are two known mechanisms through which a disk galaxy could acquire a bar: (1) a global instability or (2) orbit trapping. The path adopted depends on the mass distribution.

We find a global instability, with no ILR (initially), when the density profile has a large, quasi-uniform core. The global instability occurs on an orbital time scale, and therefore gives rise to a bar immediately in any disk that finds itself in an unstable regime. Such a situation could arise as the mass of the disk increases as primordial gas cools in a protogalactic halo and settles into rotational balance.

Orbit trapping, on the other hand, is the only viable mechanism to form a bar in a galaxy with a steep, inwardly rising density profile. This mechanism is also generally quite fast (see Lynden-Bell 1979 for an alternative) but requires a trigger, such as a mild tidal interaction (e.g., Noguchi 1996) or strong spiral patterns caused by the build up of significant quantities

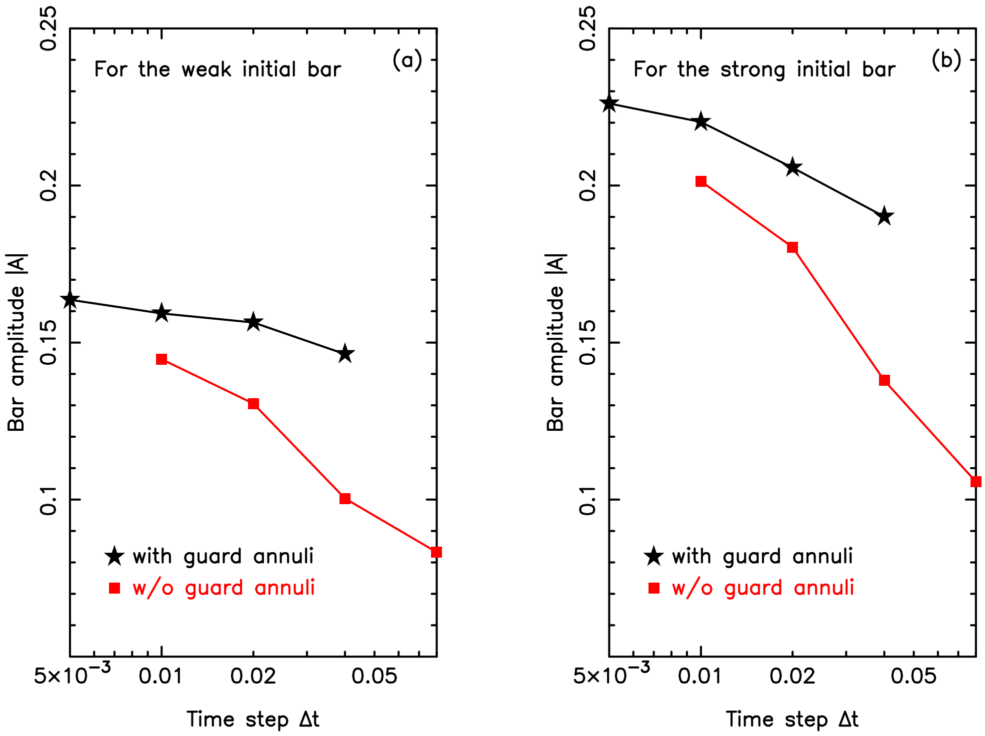


Fig. 1.3. The amplitude of the bar at a fixed time (~ 3.5 Gyr) after the introduction of a 2% disk mass CMC as the time step is varied (lower curves). The upper curves show the amplitude when the time step for orbit integration is sub-divided in nested guard annuli around the CMC.

of new, low-velocity dispersion material, in the disk (Sellwood 1989; Sellwood & Moore 1999). But isolated disks having dense centers are able to survive for long periods without making bars (Toomre 1981; Sellwood & Evans 2001).

As galaxies form, the mass distribution is dominated by the dark matter halo at first. If the halo has a large, low-density core, we should expect a bar to form once the disk mass begins to dominate in the center. Bars that may develop in halos with density profiles that rise steeply toward the center are formed through orbit trapping in the early, gas-rich disk. The evolution in the two cases is shown in Figure 1.4, and the extensive differences are summarized in Table 1.1.

Figure 1.4*a* shows that a large bar forms in the disk when the halo has a soft core ($\rho_{\rm halo} \rightarrow$ constant as $r \rightarrow 0$). Soon thereafter it undergoes a collective buckling (aka fire-hose) instability, caused by the anisotropy of the velocity distribution between the in-plane and vertical velocity dispersions (Toomre 1966; Raha et al. 1991; Merritt & Sellwood 1994). The saturation of this instability converts some of the radial motion into vertical, causing the bar to weaken and to become thicker than the disk from which it formed (see also Combes & Sanders 1981). It seems likely that any gas in the bar region would be driven still closer to the center by this event, although we are unaware of any simulations of gas in a buckling stellar potential.

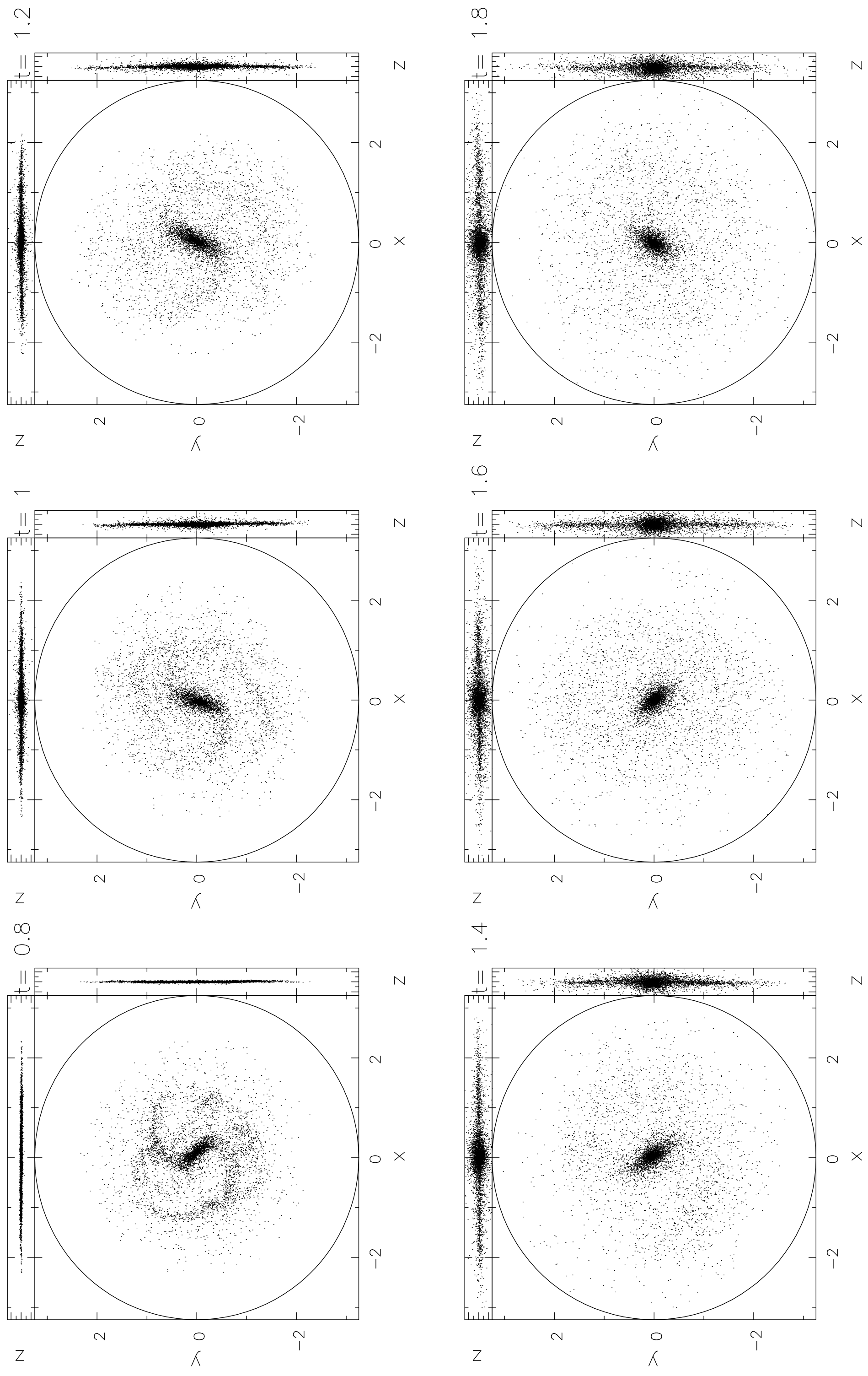


Fig. 1.4. (*a*) The evolution of the disk components in two simulations with different halos. Times are in Gyr and lengths in kpc. A simulation with a soft-core halo profile ($\rho_{\mathrm{halo}} \rightarrow$ constant as $r \rightarrow 0$).

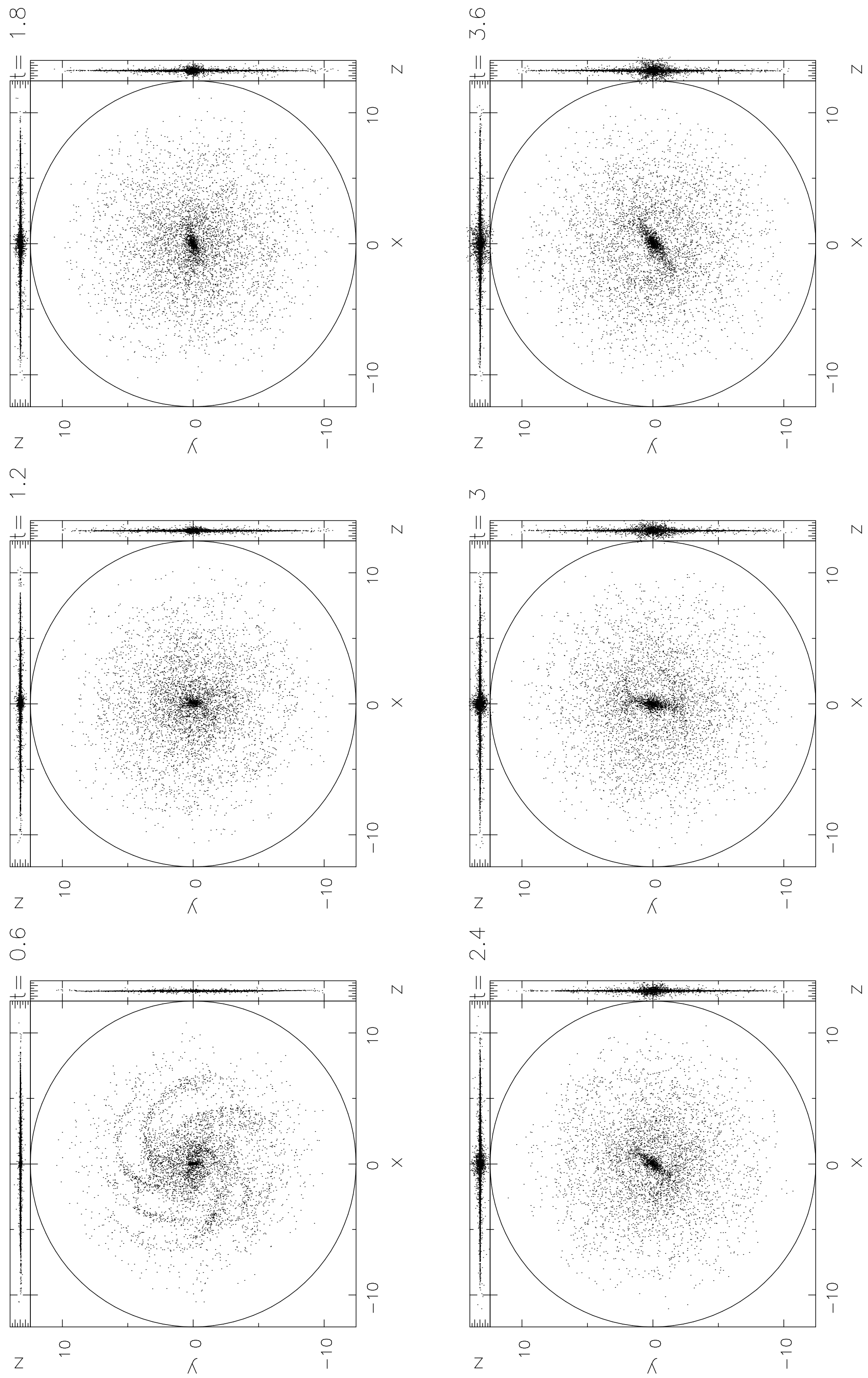


Fig. 1.4. (*b*) As in (*a*), but for a halo with a cusped density profile ($\rho_{\rm halo} \propto r^{-1}$ as $r \to 0$).

Table 1.1. *Differences between the Bars Formed in Two Different Halos*

	Soft core	Cusped halo
Initial bar	large	short
ILR	not initially	yes
Major buckling event	yes	no
Later evolution	smaller and weaker	growing

The bar in the cusped halo ($\rho_{\rm halo} \propto r^{-1}$ for small r), on the other hand, is short at first and grows in length over time (Fig. 1.4*b*). It also thickens somewhat, but because it grows gradually, it does not undergo a severe bending convulsion at any stage.

Gas can be driven deep into the center in the soft-core case, where no ILR is present (initially), and then probably be further compressed by the buckling event. These two successive dynamical instabilities in the gas-rich early stages "naturally" cause a large accumulation of gas in a small volume close to the center on a short time scale. A large concentration of gas is widely believed to be a prerequisite for the growth of a central SMBH (see Shapiro 2004), but some other mechanism may be needed to remove more angular momentum before gas reaches the density required. By contrast, the initial ILR in the cusped-halo case will halt gas inflow at some distance from the center, and the gentle flexing that thickens the bar is unlikely to have much effect on its radial distribution.

The mass of gas accumulated in the center does not have to be very large ($\lesssim 2\%$ of the disk mass) to change the global potential in the soft-core halo by enough to introduce an ILR (Sellwood & Moore 1999). As soon as the ILR is created, further gas supply to the center is shut off.

Thus dynamical evolution of the gas in the soft-core halo case suggests a picture for the origin of QSO activity that has several appealing features: it creates massive concentrations of gas in galaxy centers at the time of galaxy assembly, with a mass perhaps related to the bulge (see below), and a reason the fuel supply is shut off quickly. Note also that the SMBH mass need not be as large as that of the CMC from which it is created, indeed it would be surprising if it were; a larger fraction will form stars and some may be expelled in a wind.

Attractive as it is, such a picture is incomplete for two very obvious reasons: (1) not all SMBHs are in barred galaxies, and (2) it seems to be established that the brightest QSOs are found in merging or elliptical (i.e., post-merger) galaxies (e.g., McLure et al. 1999).

Taking the second point first: It seems likely that at least one galaxy in a merging pair must already host a SMBH in order to make a bright outburst. A bar, and any associated ILR barrier, will be destroyed in the merger, allowing plenty of fresh fuel to be driven inward—this time by the non-axisymmetric forces from the ongoing merger. Since the QSO is reignited, and the mass of the SMBH increases from its previous value, we must expect the brighter QSOs to be found in merging, or post-merger galaxies.

1.8 SMBHs in Non-barred Galaxies

The other problem is the absence of bars in some galaxies with SMBHs. Gas inflow in the early bar creates a CMC from which the SMBH is made. Since there is no initial ILR to stall the inflow, the gas concentration will be compact and the bar will be destroyed quickly if such a CMC exceeds $\sim 4\%$ of the disk mass (Fig. 1.1). However, it is likely that an ILR will form well before the central mass reaches this value, limiting the maximum compact mass that can be achieved.

The bar is weakened substantially by a CMC of $\sim 2\%$ of the disk mass (Fig. 1.1), making it more vulnerable to other destruction mechanisms. Sellwood & Moore (1999) found that ongoing spiral activity in the outer disk, which is not included in our present simulations, could either complete the destruction of the bar or cause it to grow again. Bars can also be destroyed in minor mergers (e.g., Gerin, Combes, & Athanassoula 1990).

Van den Bergh et al. (1996) suggest a deficiency of bars in all galaxies at $z > 0.5$, although the claim is disputed (e.g., Sheth & Regan 2004). There is no doubt that some bars can be missed in blue images (Eskridge et al. 2000; Dickinson 2001), but van den Bergh et al. (2002) vigorously defend the deficiency. New data from the ACS on *HST* will soon settle the question. If the deficiency is real, a second bar must be formed later to account for their present abundance.

1.9 Pseudo-bulges

An appealing by-product of bar dissolution is that the stars which were in the bar form an axisymmetric (pseudo-)bulge component in the galaxy center. Figures 1.5 and 1.6 are made from the particle distribution at a time after a strong bar has been totally destroyed by a 5% central mass. The projected density distribution (Fig. 1.5), which started exclusively in a disk, reveals a distinct central bulge that is only slightly flattened in the inner parts. The projected density profile of the model at this time (Fig. 1.6*a*) suggests two separate components, even though all particles started in a single disk component. Two distinct components are also seen in the volume density profile (Fig. 1.6*b*), which also shows the profiles of the rigid central mass and the halo components. (The spherical average used in this plot is appropriate for the bulge, but obviously not for the disk.)

Norman et al. (1996) show that such a pseudo-bulge has a high degree of rotational support, and the velocity field is cylindrically symmetric, as observed (Kormendy 1993).

1.10 Halo Mass Profiles

It would be inappropriate here to review the current controversy over the cosmologically predicted dark matter halo density profiles in galaxies. The solution to the serious discrepancy between the predicted and the observed density profiles is far from clear at present. But we would like to stress that the predicted cuspy mass profiles would force an ILR in every bar when it first formed, which would preclude the formation mechanism for QSOs proposed here.

1.11 Relation to Other Models of SMBH Formation

Following Toomre & Toomre (1972), many workers (e.g., Kauffmann & Haehnelt 2000; Di Matteo et al. 2003; Hatziminaoglou et al. 2003) argue that SMBHs form in mergers, which characterize galaxy formation in cold dark matter (CDM) Universes (e.g., Wechsler et al. 2002). Such an idea has difficulty accounting for SMBHs in galaxies that have long avoided significant mergers; examples include the Milky Way and those possessing pseudo-bulges (Carollo 2004).

The picture proposed here operates in every galaxy in which the disk is massive enough to form a bar through a global instability, and therefore accounts for the existence of SMBHs

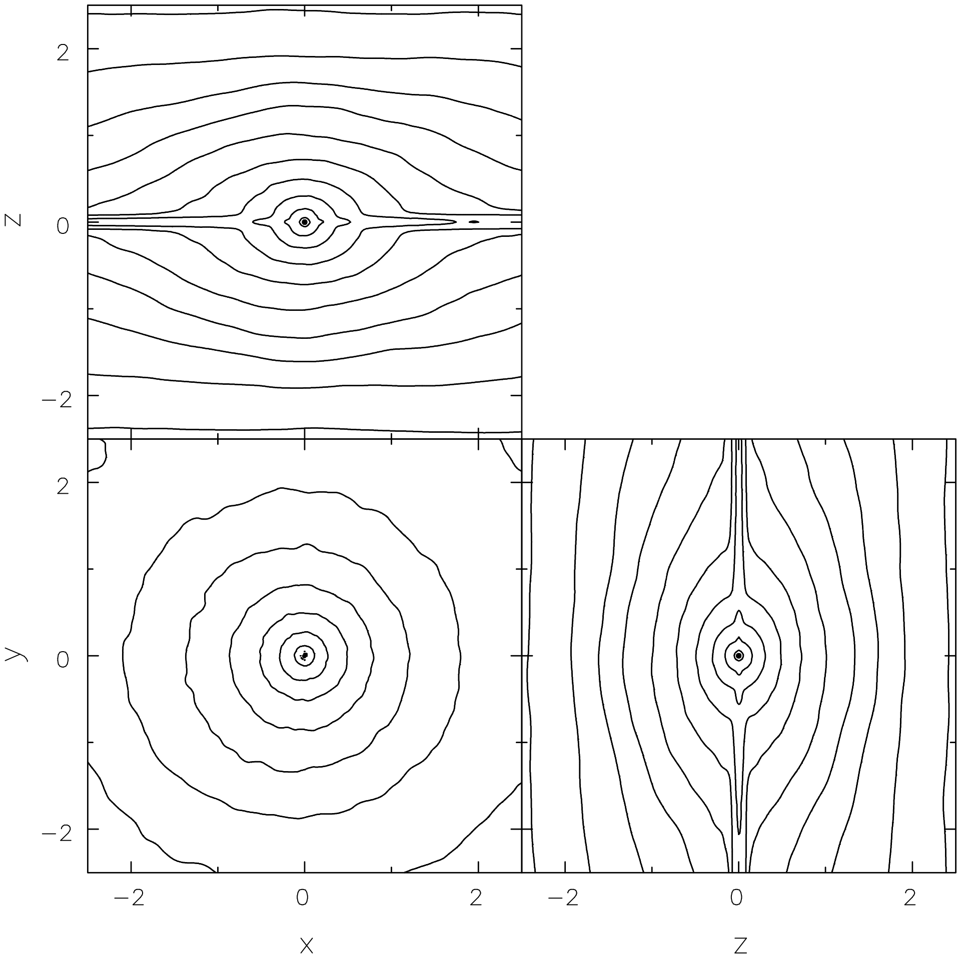


Fig. 1.5. Contours of the projected density of the inner particle distribution in 3 projections after a strong bar is fully destroyed. Distances are reckoned in units of the exponential scale length of the original disk. Notice the bulgelike feature in the edge-on views.

in every $L \gtrsim L_*$ galaxy. However, the two proposals are not mutually exclusive, and we suggest that the seed SMBHs formed by our mechanism are required to be present in the merging fragments in order to produce a bright outburst. The larger SMBHs in giant elliptical galaxies must have grown substantially during the mergers that formed them.

Furthermore, the idea of angular momentum removal by bar formation would be of help in making SMBHs by direct collapse, as discussed by Bromm & Loeb (2003), for example.

1.12 Conclusions

Inflow in barred galaxies today is arrested at a nuclear ring, which is identified as the inner Lindblad resonance (ILR) of the bar. Theoretical predictions of possible further inflow interior to the ring are not yet mature, but the evident nuclear rings in many *HST*

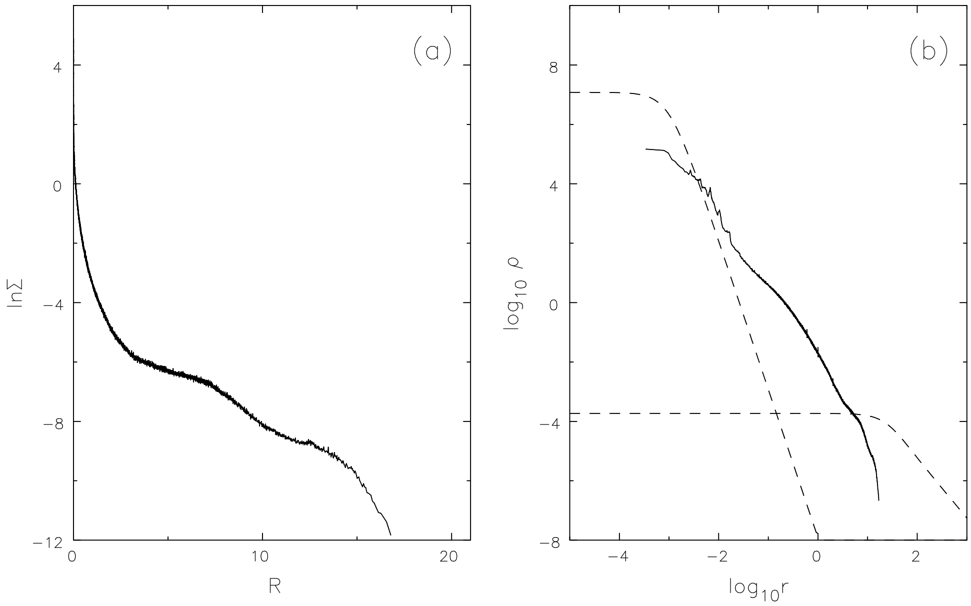


Fig. 1.6. The density profile of the particle distribution (solid curves) after a strong bar is fully destroyed. Panel (*a*) shows the face-on projected surface density of the disk and bulge, while panel (*b*) shows the volume density. The dashed curves in panel (*b*) show the density profiles of the central mass and the halo. The unit of distance is again the scale length of the *original* exponential disk.

images and mm interferometer maps imply that gas drains from the ring at a much slower rate than it arrives from larger radii. It is likely the inflow rate inside the ILR ring is little different from that in the nuclear regions of unbarred galaxies.

If bars can form without ILRs in the early Universe, then gas can be driven farther into the centers of galaxies. Gas in a bar-unstable, young galaxy disk is driven into the center by two successive instabilities: the usual bar instability, followed by a buckling instability. The gas concentration in these gas-rich early stages is likely to be large, so these instabilities deliver a substantial mass of gas to within $\lesssim 100$ pc of the galaxy center. While bar flow removes a large fraction of the angular momentum from the gas, other mechanisms, as yet unclear, are required to reduce it still further before an SMBH can form. We simply assume that an SMBH is created in every galaxy in which the disk becomes massive enough to become bar unstable.

The gas inflow itself alters the mass distribution enough to create an ILR where none previously existed, shutting off further gas supply to the nuclear region. It is likely that only a fraction of the gas driven into the center collapses to form the SMBH; probably a larger fraction will form stars, while some might escape in a wind. Any remaining gas that can accrete onto the SMBH will power a low-luminosity QSO for a while.

This picture of SMBH formation accounts for the coincidence of the QSO epoch with that of galaxy formation, the fact that SMBHs are found only in the centers of galaxies, and the short lifetime of QSO activity, because inflow is shut off by the creation of an ILR. The modest SMBHs formed in this way are the seeds for stronger outbursts that must occur when fresh gas is supplied during mergers.

Sellwood & Moore (1999) originally hoped that a further consequence of the initial CMCs that make the SMBHs would be the destruction of the bar to make a small bulge. Unfortunately, we now find that the CMC mass needed to dissolve the bar entirely is larger than could be assembled by gas inflow down the bar; the ILR probably intervenes to shut off the inflow at about half the critical mass for bar destruction. Bars can still be destroyed later, creating a bulgelike component, but this event is decoupled from the initial SMBH formation, which implies that our picture probably cannot hope to offer a simple understanding of SMBH systematics.

Our model of SMBH formation requires the dark matter halos, in which the galaxies form, to have large cores—the instabilities that create the central gas concentration do not occur if the disk forms in a cusped halo. As there are a number of lines of evidence to suggest that the cusped halos predicted in CDM cosmology are not present in real galaxies, we do not regard this requirement to be at all unrealistic. It does, however, preclude predictions of the epoch and rate of QSO activity until whatever is wrong with the CDM prediction is corrected.

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