

# On The Formation of Disk Galaxies and Massive Central Objects

J. A. Sellwood<sup>1</sup> and E. M. Moore

Department of Physics and Astronomy, Rutgers, The State University of New Jersey, 136

Frelinghuysen Road, Piscataway, NJ 08854-8019

sellwood@physics.rutgers.edu

Rutgers Astrophysics Preprint 230

Accepted to appear in *The Astrophysical Journal*

---

<sup>1</sup>*Isaac Newton Institute for Mathematical Sciences, Cambridge University, 20 Clarkson Road, Cambridge CB3 0EH, UK*

## ABSTRACT

We propose that massive central objects form in the centers of the bars which must develop in young high-surface density galactic disks. Large-scale dynamics shuts off the growth of the central mass before it reaches  $\sim 2\%$  of the disk mass at the time, but this mass is sufficient to weaken the bar substantially. Subsequent evolution of the galaxy can either complete the destruction of the bar or cause it to recover, depending upon the angular momentum distribution of later infalling material. We produce massive, fully self-gravitating disks having roughly flat rotation curves which are quite stable. If at least part of the central masses we require constitute the engines of QSOs, then our picture naturally accounts for their redshift dependence, since the fuel supply is shut off by the development of an inner Lindblad resonance. A prediction is that massive objects should not be found in halo dominated galaxies, such as low-luminosity, or low-surface brightness galaxies.

*Subject headings:* galaxies: active — galaxies: evolution — galaxies:  
halos — galaxies: kinematics and dynamics — Galaxy: halo —  
Galaxy: structure

## 1. Introduction

It is widely believed that galaxy disks form as gas cools and settles into rotational balance in massive dark matter halos (White & Rees 1978; Fall & Efstathiou 1980; Gunn 1982; Ryden & Gunn 1987; van der Kruit 1987). This broad picture has been further developed by Dalcanton, Spergel & Summers (1997) and Mo, Mao & White (1998) who, however, continue to employ Mestel's (1963) simplifying assumption that infalling matter conserves its detailed angular momentum distribution. Such a treatment is inadequate once the disk becomes massive enough to be self-gravitating because angular momentum will be redistributed by non-axisymmetric instabilities. While the consequences of such instabilities have not been fully worked out, Dalcanton et al. plausibly suggested that they could be responsible for the formation of bulges. On the other hand, Mo et al. conclude that high mass disks are unphysical on the obscure grounds that “only dynamically stable systems can correspond to real galaxy disks.”

If the disk in a high-surface brightness (HSB) galaxy is in fact the dominant mass component in the inner parts, for which there is considerable evidence (see §2), then it must have become self-gravitating at an early stage. It is therefore an issue of some urgency to determine what really would happen as a dominant disk grows. The purpose of this article is to pursue this question a little further.

It is well known that bars form in rotationally supported, massive disks that lack a strong central density concentration. Bars formed in this manner are generally long lived, but they can be destroyed in at least two ways: by the infall of a moderate mass companion into (or its passage through) the inner disk (e.g., Pfenniger 1991; Athanassoula 1996) or, more interestingly, through the growth of a central mass (Hasan & Norman 1990; Norman, Sellwood & Hasan 1996).

Here we propose that every massive disk formed a bar in its early stages and that many,

though probably not all, of these bars were destroyed by the development of a massive object in their centers.

It seems reasonable to expect that a newly formed bar in a young, gas-rich disk will drive substantial inflow (Noguchi 1988; Barnes & Hernquist 1991; Friedli & Benz 1993; Heller & Shlosman 1994). The distance from the center at which the flow stalls depends both on where the quadrupole field of the bar weakens and whether an inner Lindblad resonance (ILR) exists to halt the flow (Athanasoula 1992). Inflow is halted at an ILR because inside that resonance the closed orbits in the potential are aligned perpendicular, instead of parallel, to the bar (e.g. Binney & Tremaine 1987, §3.3). The torque from the bar on the gas, which arises from its offset distribution with respect to the bar major axis, decreases rapidly within this resonance.

Since the halo has a large low density core, the disk which forms in the early stages is likely to have a gently rising rotation curve and the bar will lack an ILR. Gas can therefore be driven as far inwards as the torques from the bar can achieve. It is difficult to predict what will happen when large quantities of gas accumulate in a small volume at the center of a galaxy, since it depends on the physical state of the gas, its ability to fragment and form stars, energy feed-back, and other poorly-understood processes. For the purposes of this article we simply propose that a gravitationally bound object is formed that is massive enough to weaken the bar (§3). The precise nature of the object is unimportant for the dynamics of the galaxy; a dense star cluster is one possibility, but it is also natural to think that at least a fraction of the mass may collapse to create the engine of a QSO, an idea we explore in section 5.

## 2. Evidence for maximum disks

The radial distribution of mass in a disk galaxy is strongly constrained by its rotation curve. The separate contributions from the individual stellar populations and dark matter (DM) are not easily disentangled, however, especially since there is generally no feature to indicate where the component dominating the central attraction switches from luminous to dark matter (Bahcall & Casertano 1986).

### 2.1. Rotation curve fitting

Kalnajs (1983), Kent (1986), Buchhorn (1992), and Palunas & Williams (1998) all show that the shapes of the inner rotation curves of most (mostly high surface brightness, HSB) galaxies are remarkably well predicted by the visible matter if a constant  $M/L$  is assumed for the disk (and bulge). In these studies, mass discrepancies indicative of the DM halo contribution become pronounced only in the outer parts.

Palunas & Williams worked in the I-band, which Worthey (1994) finds is least sensitive to metallicity. Figure 1 shows the distribution of  $M/L_I$  values they obtained for their maximum disk fits, for  $H_0 = 60 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . (Theirs was not a properly selected sample and statistical inferences could therefore be misleading, but systematic effects in the sample selection that would compromise this histogram seem unlikely.) Some galaxies were clearly barred, despite being classified as SA in the catalogs, and the distribution of values for these cases is shown separately. There is no significant offset between the two distributions.

More than half their values lie in the range  $1.5 < M/L_I < 2.5$ , although the distribution has broad tails on both sides. (The spread seems too great to be attributable to distance errors alone.) Their values therefore are consistent with the  $M/L_I \sim 1.5 - 2$  predicted by Jablonka & Arimoto (1992) for continuous star formation and by Worthey (1994) for a

population with a mean age of  $\sim 5$  Gyr. Casertano & van Albada (1990) find that the  $M/L_B$  varies with color in the manner predicted by earlier stellar population models.

If DM were to be important at all radii, its radial distribution would need to be such that the shape of the inner rotation curve is little different from that predicted by the light (van Albada & Sancisi 1986; Freeman 1992), presenting a fine-tuning problem for each galaxy. Local features, such as spiral arms, often reproduce small-scale structure in the rotation curve but the stronger argument stems from the overall shape of the rotation curve. The strongest cases are the few known galaxies for which the rotation curve declines somewhat outside the optical disk (e.g. Casertano & van Gorkom 1991). Nevertheless, the argument is not always regarded as compelling (e.g. van der Kruit 1995).

## 2.2. Barred galaxies

Barred galaxies offer ways to estimate disk masses that are independent of rotation curve fitting. Weiner et al. (1998) model the gas kinematics in the barred galaxy NGC 4123 by calculating 2-D gas flows in a model potential derived from the I-band photometry. They find that the strength of the observed non-axisymmetric flow pattern can be matched only by making the bar so massive that there is no slack in the rotation curve to permit significant quantities of DM in the inner galaxy. Their best fit model has  $M/L_I = 2.0$  with values in the range  $1.6 \leq M/L_I \leq 2.4$  being acceptable, in impressive concordance with Figure 1.

A second argument is presented by Debattista & Sellwood (1998), who show that bars are slowed dramatically as they lose angular momentum even in moderate density halos. Only if the halo central density is low, and the disk is maximal, can rapid braking be avoided and pattern speeds remain consistent with those in real barred galaxies.

### 2.3. Global stability

Ostriker & Peebles (1973) suggested, in a frequently-cited argument against maximum disks, that the global stability of unbarred disk galaxies requires a massive halo. Their original parameter,  $t = T_{\text{rot}}/|W|$ , provides a remarkably succinct summary of many results, both numerical and analytic, on the stability of disks in potentials that have significant harmonic cores. The criterion is clearly too simple for a number of reasons and several attempts have been made to refine it (e.g., Christodoulou, Shlosman & Tohline 1995 and references therein).

Efstathiou, Lake & Negroponte (1982, ELN) proposed another simple stability criterion based on an extensive set of numerical simulations. Once again, their criterion requires substantial DM fractions to inhibit bars. Unfortunately, it is now clear that the ELN criterion omits the important stabilizing influence of a dense center. Both linear stability work (Zang 1976; Toomre 1981; Evans & Read 1998) and more careful  $N$ -body simulations (Sellwood 1989 and this paper) show that linear bar-forming instabilities can be avoided altogether in disks with minimal DM halos, provided only that the rotation curve has a steep inner rise. Toomre (1981) clearly states the reason why a dense center is important and his argument is also explained by Binney & Tremaine (1987, ch. 6). Sellwood (1989) was even able to identify the numerical problem (excessive particle noise) that caused ELN to miss this important factor.

In conclusion, no simple criterion has yet been formulated that encapsulates all known global stability results but it is clear that any such criterion cannot be based purely on the halo mass fraction. Generally, unbarred galaxies having gently rising rotation curves are still thought to require substantial halo mass interior to the disk edge. On the other hand, a massive disk can be bar-stable even in a minimal halo when its rotation curve rises steeply close to the disk center.

## 2.4. Other Evidence

Multi-arm spiral patterns develop in simulations in which the halo dominates the central attraction everywhere, which Sellwood & Carlberg (1984) argued was consequence of swing amplification (Toomre 1981). This local stability property was exploited by Athanassoula, Bosma & Papaioannou (1987) who showed that the order of symmetry of the spiral arm pattern in many cases was consistent with near maximum disks.

It is often argued that the Milky Way does not have a maximum disk (e.g. Kuijken 1995) and that if the maximum disk hypothesis fails for the Galaxy, where we have the only real hope of a direct estimate of the disk density, it is also unlikely to be valid where constraints are weaker. Sackett (1997) points out that this view is strongly sensitive to the adopted scale length for the disk. Furthermore, Sellwood (1998) and Englmaier & Gerhard (1998) suggest that the right M/L for models of the Milky Way based upon the COBE NIR photometry again leaves little room for DM in the inner Galaxy.

Others claim to find evidence for large quantities of DM in the inner parts of galaxies. We find Bottema's (1993) arguments unconvincing because they invoke general disk properties, such as a smooth exponential light profile and/or a constant central surface brightness, etc. The often substantial departures from a simple exponential light distribution, which are usually most pronounced in the massive inner disk, cannot be ignored.

## 2.5. Implications

Most of the above evidence is based upon bright, HSB galaxies and suggests that in these cases DM halos have low central densities and large core radii. The rotation curves of low-luminosity galaxies (e.g. Broeils 1992) and of low-surface brightness (LSB) galaxies (e.g.



de Blok & McGaugh 1996), on the other hand, do not have the shape predicted from the light distribution and therefore must have significant dark matter fractions right to their centers. The slowly rising rotation curves of these systems provide more direct evidence of a large core to the halo mass distribution.

Navarro, Frenk & White (1996, hereafter NFW) predict a cuspy density profile for collisionless DM halos from their careful cosmological simulations, a result first hinted at by Dubinski & Carlberg (1991). NFW concede that their mass profile is inconsistent with the observed mass distributions in low-luminosity galaxies (but see Kravtsov et al. 1998), and it also fails for LSB galaxies (de Blok & McGaugh 1996). But Navarro (1997) claims both that large HSB galaxies do have NFW halo profiles and that DM dominates the mass even in the bright inner galaxy. The evidence summarized above does not support Navarro’s claim, and it seems that few, if any, real galaxies have the cuspy DM halo profile predicted by these large-scale structure simulations. It is unclear how this inconsistency will be resolved.

The dominance of luminous matter in the inner parts of large HSB galaxies leads to the well-known conspiracy (Bahcall & Casertano 1986) in which the circular velocity from the luminous material in the inner parts is generally differs little from that inferred for the dark matter in the outer parts. Some galaxies with declining rotation curves are known (Casertano & van Gorkom 1991) but the drop is rarely more than 10%. Blumenthal et al. (1986) note that halo compression by baryon infall can lead to flat rotation curves, but the similarity of the circular speeds even for extreme maximum disks has no convincing explanation.

### 3. Simulations

In this section, we present simulations of disk galaxy formation in low density halos. The dynamics is largely controlled by the dominant mass component, the stellar disk, but here we identify two gaseous processes which are also of importance to the large-scale dynamics: dissipation to provide fresh disk-like material on near circular orbits in the gravitational potential well and strong shocks in bars to drive gas inwards and build up large central mass concentrations.

Simulations of coupled gaseous and stellar dynamics present a much greater computational challenge than do those of the stellar component alone. Ambitious calculations to model both components at once have been presented by Navarro & Steinmetz (1997) and many others. These expensive calculations attempt to model not only the collisionless stellar component, but also gas cooling, radiative heating, shocks, infall, star formation, energy feed-back to the gaseous material, etc. Many of these processes occur on scales too small to be meaningfully resolved and the physics of star formation and energy feed-back in particular is poorly understood; the simulators simply include ad hoc rules to mimic them. Moreover, the important process of shock-driven inflow in bars is sensitive to numerical viscosity (Prendergast 1983) and therefore demands a high quality treatment.

Here we simplify the problem by including only those processes of importance to the large-scale dynamics. Sellwood & Carlberg (1984), Carlberg & Freedman (1985), Villumsen & Gunn (1987), and Toomre (1990) have established the importance of dissipation in driving evolution in galaxy disks and have shown that for dynamical purposes, all that is required is a steady reduction of the rms peculiar velocity of particles to keep the system evolving. Gas inflow in bars has been shown to occur in both theoretical work (Prendergast 1983; Athanassoula 1992; etc.) and in practice (Quillen et al. 1995). Other gas-dynamical processes have little effect on the mass distribution or its kinematic properties, such as

flow through spiral shocks and star formation, and therefore scarcely affect the large-scale dynamics: settled gas moves on essentially the same orbits as do stars since the generally mild spiral shocks have a minor effect on the shape of the streamlines, while conversion of gas into stars does not significantly change the orbit. We therefore employ a collisionless  $N$ -body code for our problem; the two gaseous processes that are of dynamical importance have well understood consequences which can be included in a simplified way (§§3.1 & 3.2) while other processes can be ignored.

Our models improve upon the work of Dalcanton et al. and Mo et al. in three respects: (1) we follow the evolution of a galaxy as the disk mass rises, allowing instabilities to develop and run their course, (2) we adopt a DM distribution more consistent than the NFW profile with those observed, and (3) we include the effect of a central massive object.

### 3.1. Disk formation

We mimic the gradual formation of a massive disk by adding fresh particles on circular orbits in the mid-plane. This crude procedure was originally found effective by Sellwood & Carlberg (1984). Further experiments by Sellwood & Carlberg (unpublished) and Carlberg & Freedman (1985) have demonstrated that the formation of spiral disturbances, the build-up of random motion, and the redistribution of angular momentum are scarcely affected by the details of the procedure adopted to mimic the process of dissipation.

Large-scale structure simulations predict unrealistic halos and are saddled with a celebrated “overcooling problem” (e.g. Navarro & Benz 1991), which is essentially that the specific angular momentum of the baryonic matter is too low. These difficulties suggest that such simulations cannot make reliable predictions for the angular momentum distribution of infalling material, or the rate at which it should arrive. Moreover, energy feed-back from

star formation in the disk has an indeterminate effect on both quantities. Our rules for the accretion rate and for the initial angular momenta of fresh particles are therefore necessarily arbitrary.

It seems reasonable to assume that the inner disk builds up quite rapidly and that the mean angular momentum of late arriving material is greater than that which was accreted at an early stage. We have experimented with a few different rules that embody both these principles and found that the final mass distribution is not strongly sensitive to the accretion rate. The mean angular momentum of the accreted material does affect the outcome, but minor changes to its distribution make little difference to the behavior. The rates at which we add mass are quite high in the early stages, as much 10% of the “final” mass of the disk per final rotation period in most cases; we have experimented with decreasing this rate substantially during the later stages. The adopted rule for each of the two models reported here is given in Table 1.

We give each added particle the local orbital velocity determined from azimuthally averaged central attraction at the chosen radius and zero velocity in the radial and vertical directions. We determined the initial  $z$  coordinate from an estimate of the local mid-plane position, indicated by where the vertical force passes through zero.

To save a little effort, we begin our calculations with a small self-gravitating disk which we imagine to have formed at an early stage in the center of a protogalaxy. Our initial model has no strong density concentration and no bulge. In the experiments reported here, we adopt a Kuz'min-Toomre model for our initial disk which has the radial surface density profile

$$\Sigma(R) = \frac{M}{2\pi a^2} \left(1 + \frac{R^2}{a^2}\right)^{-3/2}. \quad (1)$$

We adopt the initial disk mass,  $M$ , and length scale,  $a$ , as our units of mass and length. We truncate the disk at  $R = 5a$ , spread the particles vertically with an rms thickness of  $0.05a$ ,

and assign suitable initial velocities to the particles to create an equilibrium model with Toomre’s  $Q \simeq 1.5$ . Wide variations around these choices make little difference to the late time evolution of our models. We evolve this initial disk until after the central mass has reached its final value before beginning to add fresh particles.

### 3.2. Central mass

As discussed above, a strong bar drives gas inward to produce a central mass concentration. We consider the possible fate of the dense gas concentration produced by the inflow in §5, but for the present purposes the only aspect of relevance to the large-scale dynamics is the accumulation of mass in the center.

Unreasonably high central masses ( $\sim 5\%$  of the disk mass) are needed to destroy the bar completely and are unlikely to be achieved in reality. Gas inflow is halted at the ILR, which is certainly present once the central mass has reached a mass of  $\sim 1 - 2\%$ , cutting off the supply of material for further growth. We therefore limit the mass of the central object to  $\sim 1.5\%$  of the initial disk mass. This limit is sufficient to cause a significant weakening of the bar, to about half the amplitude which results if no central mass is imposed.

We increase the mass of a single central particle having the density profile of a Plummer sphere. The effect the central mass has on the bar depends to some extent on its core radius: For a fixed final mass, we find that the bar is weakened to a much lesser extent when its core radius exceeds  $0.05a$  but reducing it below this value causes the bar to weaken only slightly more, as might be expected. We were unwilling to employ a very small core radius since that would make the calculations more expensive by requiring a shorter time step.

In the two experiments reported here, we set the core radius to  $0.05a$  and increase the mass of the central particle whenever the ratio  $\alpha_2/\alpha_0$  exceeds some threshold value. Here

the  $\alpha$ s are coefficients of a Fourier expansion of the density over some inner radial range. We choose these parameters so as to obtain a final mass of  $\sim 1.5\%$ ; the adopted values for each model are given in Table 1.

### 3.3. Halo

Since we were anxious to model maximum disks, and wished to avoid including rigid potentials if possible, our first models lacked a halo component. This seemed justifiable, since most halo mass in a maximum disk model lies beyond the disk edge and, when spherically distributed, exerts no forces on the disk. We found, however, that irrespective of the amount of mass added to the outer disk, the rotation curve always declined in our halo-less models. The massive disk always developed strong one- and two-armed spiral patterns that caused the central density to rise ever higher while spreading material to ever larger radii, thereby defeating our objective of creating a realistic rotation curve.<sup>2</sup>

We were therefore forced to include a DM halo in some way. We add supplemental forces from a rigid potential of the form

$$\Phi_{\text{halo}} = \frac{V_0^2}{2} \ln \left( 1 + \frac{r^2}{c^2} \right), \quad (2)$$

which yields an asymptotically flat circular velocity of  $V_0$  for  $r \gg c$ , with  $c$  being the “core radius”. Setting  $c = 30a$ , 2.5 times the largest radius at which we added particles, reduced the spreading of the outer disk dramatically. Since the peak circular velocity from our disk is about  $0.6(GM/a)^{1/2}$ , we generally choose  $0.6 \leq V_0(a/GM)^{1/2} \leq 0.8$ ; our results are little affected by the precise value within this narrow range.

---

<sup>2</sup>Note that such behavior challenges suggestions that the flat rotation curves of galaxies could be caused by an outwardly increasing M/L in the disk or by the existence of large quantities of cold gas in the outer disks (Pfenniger, Combes & Martinet 1994).

We include this diffuse halo as a rigid component because to represent it with live particles would severely compromise our spatial resolution in the disk. By keeping it rigid, we introduce a number of approximations, which we do not expect to affect our conclusions. First, we exclude the possibility of disk-halo interactions, such as angular momentum exchange (Weinberg 1985) but this is unlikely to be significant for such a large core radius halo (Debattista & Sellwood 1998). Second, we exclude the compression of the halo as the disk mass builds (Barnes & White 1984). Third, a substantial lop-sidedness in the distribution of active particles could also give rise to unphysical behavior, but has fortunately not developed in any of our models with halos. This final concern forced us to fix the position of the central mass also.

### 3.4. Numerical details

We use the 3-D polar grid-based  $N$ -body code described by Sellwood & Valluri (1997). The numerical parameters for the models presented here are given in Table 1. Reasonable variations around the adopted values do not lead to significantly different behavior.

### 3.5. Results

We first describe the results from an experiment (model 1) which is typical of our more successful models. All quantities from here on are expressed in units such that  $G = M = a = 1$ .

As expected, the initial massive disk rapidly forms a bar in the usual way. Because the model is not centrally condensed, the pattern speed need not be very high to avoid an ILR, as shown in Figure 2(a).

The central density of the model rises in response to the growing central mass making a small bulge of much larger mass than that of the imposed mass. The bar amplitude, assessed as  $\alpha_2/\alpha_0$ , abruptly drops to about half its peak as the central mass reaches 1.4% of the disk mass in this case. At this point, the mass distribution is sufficiently centrally condensed that the bar has probably acquired an ILR, as suggested in Figure 2(b). It should be noted, however, that the curves of  $\Omega - \kappa/2$  drawn in this Figure are computed from the azimuthal average of the central force in this strongly barred potential. They do not, therefore, give a *reliable* guide to the existence of the perpendicularly aligned orbit family, which is the only sure indication of a generalized Lindblad resonance in strongly perturbed potentials (Contopoulos & Grosbøl 1989).

Once we stop growing the central mass, the rotation curve of the model (Figure 3) has a high inner peak and a deep dip before rising again as the halo contribution picks up. We began to add fresh particles at a steady rate, from time 160, placing them on circular orbits in the radial range  $8 < R/a < 12$  only, in line with our expectation that later arriving material will have somewhat larger angular momentum. We added 8 particles at every time step, or  $\dot{M} = 5 \times 10^{-3}$  in our units – i.e. a mass equal to one tenth the final disk mass about every rotation period at  $R = 10$ . Strong spiral patterns develop (Figure 4) which redistribute angular momentum efficiently. Continued accretion of material causes recurring spiral activity that spreads the new material both inwards and outwards, causing the rotation curve to become more nearly flat while the inner peak rises slightly more.

The residual bar left after the growth of the central mass is short and weak. Later in this simulation it disappears almost entirely (Figure 4b), and no bar-like feature returns. The gradual disappearance of the bar seems to be caused by an interactions with strong spiral patterns in the inner disk.

By the last time shown in Figure 4, which is not the end of our calculation, the



accreted mass is four times that of the initial disk. Even though the disk created in this way is almost fully self-gravitating, it does not form a bar. The instability is inhibited both because the inner disk is dynamically hot and because of inner Lindblad resonances arising from the high central density (Zang 1976; Toomre 1981; Binney & Tremaine 1987 §6.3; Sellwood 1989; Evans & Read 1998). It is worth noting that the  $t$  stability parameter introduced by Ostriker & Peebles (1973) remains above 0.25 from time 300 to the end; the stability parameter introduced by Efstathiou et al. (1982) remains  $\lesssim 0.7$  since the disk scale length increases approximately as the disk mass.

A notable feature of this experiment is that the matter rearranges itself in such a way that the rotation curve becomes approximately flat, except perhaps for the sharp inner peak (Figure 3). We have seen this behavior in other experiments with different accretion rules. Moreover, despite concerted attempts, we have been unable to create a persisting rise in the rotation curve in a massive disk; whenever accretion created a rising rotation curve, very strong spiral patterns developed that redistributed enough angular momentum to cause the central peak to rise until a roughly flat or declining rotation curve was re-established. This result seems to be of some importance.

This experiment suggests a natural mechanism to build massive unbarred disks that have central densities high enough to suppress bar formation and a roughly flat rotation curve. It demolishes the argument by Mo et al. that self-gravitating disks could not be formed, and supports the contention by Dalcanton et al. that instabilities will form a modest bulge at the centers of disk dominated galaxies.

The galaxy we have created has a rotation curve (e.g. Rubin, Ford & Thonnard 1980), bulge size and morphological appearance resembling those of large Sc galaxies. (Indeed, Kent (1986) showed that the inner parts of precisely these same rotation curves were nicely reproduced by the radial light distribution in these galaxies.) We have produced an Sc type

galaxy probably because our simulation has mimicked the formation of an isolated galaxy. Early-type galaxies may require mergers of proto-galactic fragments, or even of small disk galaxies, to make their larger bulges.

#### 4. Barred galaxies

Since we argue that most massive disks acquire central masses which weaken or destroy their bars, we must account for the existence of a substantial fraction of strongly barred galaxies today. Before offering an explanation, we note two other related, but long-unanswered, questions presented by barred galaxies.

- The observational signature of a central density high enough that it should have inhibited a bar by Toomre's (1981) mechanism is the existence of a nuclear stellar or gaseous ring. Many barred galaxies have nuclear rings with diameters of several hundred parsecs (Buta & Crocker 1993), which are widely believed to form where gas inflow along the bar is halted at an inner Lindblad resonance (ILR). There is abundant evidence for gas build up in nuclear rings (e.g. Helfer & Blitz 1995; Rubin, Kenney & Young 1997) and other evidence for ILR phenomena has been claimed (e.g. Knapen et al. 1995). We note also that the Milky Way, which is now believed to be a barred galaxy (de Vaucouleurs 1964; Blitz et al. 1993), has long been known to have a very dense center (Becklin & Neugebauer 1968). So why are these galaxies barred, if their dense centers should have inhibited bar formation?
- No satisfactory explanation for the observed frequency of bars has yet been proposed. Some 30% of HSB galaxies are strongly barred and perhaps an equal fraction are weakly barred (Sellwood & Wilkinson 1993). An argument that these galaxies contain somewhat less DM than do unbarred galaxies is easily dismissed by the evidence

for maximum disks in all HSB galaxies presented in section 2. Moreover, while the normal bar instability provides a natural explanation for the existence of strong bars, we are not aware of a model for the origin of weak bars.

In our picture, most HSB galaxies should have dense centers – barred galaxies should not be an exception. Here we propose that a second, and this time lasting, large-scale bar developed in some galaxies. Unlike the first bar, it is not weakened by gas inflow because the flow is halted at the ILR which prevents the central mass from increasing.

A second bar could form for one of two possible reasons. First, the stability of the disk relies on the ability of the ILR to damp incipient bar instabilities, but the resonance can be overwhelmed by large perturbations and a strong bar can result (Sellwood 1989). One possible source of large perturbations is tidal encounters (Noguchi 1987); evidence has been claimed (Elmegreen, Elmegreen & Bellin 1990) for a higher fraction of barred galaxies in dense environments where bar-triggering encounters should be more frequent.

Second, we should expect relatively low angular momentum material to be added to the disk in some fraction of galaxies. Such material will settle in the inner few kpc where it is able to re-excite a bar, as shown in Figure 5. (This model differs in several respects from that shown in Figure 4. The central mass was grown to about 1.5% of the disk mass much more quickly and accretion began at time 40. Note also that the spatial scale in the plots is different.) The short initial bar, which was weakened when the central mass formed, gradually regains strength through angular momentum exchange with fresh cool material near its outer Lindblad resonance, as occurred in previous experiments (Sellwood 1981). The distribution of angular momentum in the accreted matter will need to be known in some detail before it can be determined whether the observed distribution of bar strengths is correctly predicted by this effect.

In this picture, we expect the fraction of galaxies possessing strong bars to be similar, or perhaps somewhat less, at high redshift than in the local universe. The timescale on which the first bars are formed and destroyed is so short that we are unlikely to see many galaxies in this stage. The formation of the second bar occurs over a longer period, though still in the early life of a galaxy, and we therefore might expect to see slightly fewer in a high redshift sample. It is important that the frequency of bars in the high redshift sample should be determined from images in the rest-frame red or near-IR pass bands in which bars are most easily seen in the nearby universe.

## 5. The quasar epoch

The now standard model for QSO activity is a massive collapsed object at the center of a galaxy, proposed by Lynden-Bell (1969). Mass constraints require that such objects are active for a comparatively short time (Padovani, Burg & Edelson 1990). Small & Blandford (1992) argue, from the existence of high redshift quasars, that the massive object must grow “rapaciously” in its early stages. Quasar spectra seem to require massive objects in most bright galaxies (Chokshi & Turner 1992).

We suggest that some of the mass which accumulates at the centers of bars collapses to power quasars. If this association is correct, the onset of the quasar epoch (Schmidt, Schneider & Gunn 1995; Shaver et al. 1996) should be coincident with the formation of the first bars in disks.

The idea that large-scale stellar bars could cause massive objects to be created was already proposed by Shlosman, Begelman & Frank (1990), who suggested that the gas density could rise to the point of a second, much smaller scale, bar instability – or indeed a cascade of such events to successively smaller spatial and time scales. Haehnelt & Rees

(1993) and Eisenstein & Loeb (1995) also suggested that massive objects formed in the centers of gas rich protogalaxies, but these models do not invoke non-axisymmetric stellar mass distributions to remove the angular momentum.

The new feature of our model is that it offers a dynamical reason why nuclear activity should cease soon after the central mass becomes large enough to cut off its gas supply through the development of an inner Lindblad resonance, or (possibly) the complete destruction of the bar. The later formation of bars in a significant fraction of galaxies would not cause further nuclear activity because the central engine is shielded by the ILR.

QSOs should flare during the formation of disk galaxies, but we also expect that mergers of disk galaxies which already host central masses will lead to brighter outbursts (Lehnert et al. 1992) as the mass of the central object rises further. This seems to be required by the observation that QSOs, especially the radio-loud type, are frequently found in elliptical galaxies (Taylor et al. 1996). Mergers lead to tri-axial objects (Barnes 1992), and Merritt & Quinlan (1998) have already suggested that if the mass of the central object in a tri-axial elliptical galaxy is low, it will continue to be fed by stars on box orbits until it reaches a mass approaching 2% of the galaxy before the box orbits become stochastic and make the galaxy axisymmetric.

### 5.1. Massive central objects today

Our model suggests that supermassive objects should be found in almost every bright galaxy, except for those cases where they have possibly been ejected (Rees 1997). Magorrian et al. (1997) claim that the data on nearby galaxies are consistent with a massive object in almost every galaxy, with a suggestion that the mass of the central object is correlated with the bulge mass. Both aspects can be explained in our picture, since the dissolved bar

produces a bulge. Their estimate of an object mass that is a few tenths of a percent of the bulge mass may suggest that perhaps the supermassive object may be some  $\sim 10\%$  of the central mass concentration. It should be noted that disks will continue to increase in mass through accretion subsequent to this event. Minor mergers will also add mass, probably to the bulge.

We predict that no massive central objects should be found in DM dominated galaxies, because such galaxies would not have formed bars. In section 2 we argue that HSB galaxies are disk dominated, but it is well established that LSB galaxies cannot be (de Blok & McGaugh 1996). There is also some evidence for significant halos in low luminosity galaxies (e.g. Broeils 1992); a good local example is M33 which has a gently rising rotation curve and must therefore be halo dominated to suppress the bar instability. Happily, M33 also happens to have one of the lowest upper limits on the mass of a central object (Kormendy & McClure 1993). It should be noted that this difference is not predicted by models which invoke capture of pre-formed black holes into the centers of galaxies (e.g., Lacey & Ostriker 1985) or in purely gas dynamical models (Eisenstein & Loeb 1995; Silk & Rees 1998) in which the processes invoked do not depend on DM fraction.

## 6. Loose ends

While we hope the outline for the late stages of disk galaxy formation presented in this paper has some merit, we recognise that many crucial parts of the picture are seriously incomplete. More detailed examination of several parts may render the whole edifice untenable. Here we note several significant gaps of which we are aware.

We have simply postulated that a dense central object forms in a gas rich barred galaxy which originally had a shallow density distribution. Most bright galaxies have dense centers

today, and it seems reasonable that both dissipation and angular momentum redistribution were required to bring this about. Gas inflow along a bar is well established, but it is highly speculative to argue, as we have here, that a dense central object is built where there was not one before.

The inflow process is self-regulating, since it is halted by the ILR as soon as enough mass has accumulated in the center to produce one. The existence of an ILR in a strongly barred system cannot simply be determined from the “rotation curve” but requires the perpendicularly aligned orbits in the bar to be found (e.g. Contopoulos & Grosbøl 1989). Exactly when this family appears and how much mass can be expected to make it to the center before the valve closes is not yet known, but must be of the order of 1%. Further work in this area is needed.

Can the currently observed fractions of strong and weakly barred galaxies be accounted for naturally by a combination of interactions and accretion of low-angular momentum material? A quantitative answer to this question could be provided only from simulations of hierarchical clustering, but seems well beyond what is technically feasible today.

We argue that our models resemble large Sc galaxies both in appearance and in their rotation curve shapes. Lower luminosity Sc galaxies with gently rising rotation curves must have sufficient DM to inhibit the bar instability. It is likely that the formation of early type galaxies with dominant bulges requires some degree of merging of protogalactic fragments which has to happen at a time after the dense center is established in at least one of the fragments but while more infalling material can create a new disk. This process will also have to be modelled carefully to determine how our model is affected.

We have used an unresponsive mass distribution to represent the halo, an approximation with the limitations we listed in §3.3. It is clearly desirable to simulate a live halo to show that some initial halo mass distribution can be adopted that will allow a maximum disk to

form within it.

## 7. Conclusions

We have extended the popular picture of disk galaxy formation through the settling of gas in DM halos to address a variety of unsolved problems. We suggest that: (1) Not only can massive disks survive at the centers of low density halos, but that they naturally develop rotation curves which become flat over a wide radial range after a steep inner rise. (2) The process of developing the dense central concentration, and much more speculatively the central engine of quasars, occurs when the bar, which must form in every massive disk, drives gas inwards until the central object is massive enough to cut off the flow. (3) This amount of mass is sufficient to weaken the bar, though not to destroy it. (4) Galaxies with central mass concentrations can be barred today because either they suffered a tidal encounter or they later accreted low-angular momentum material that strengthened the bar. The second bar in a galaxy can survive, without causing the central mass to rise further or re-igniting the central engine, because inflow this time is halted at the inner ring which forms at the ILR.

If these ideas are correct, then we predict that massive objects should not be found in galaxies in which DM dominates all the way to the center.

This entire picture is speculative and requires a great deal of additional work to establish its viability. We list some of the more important loose ends in section 6.

This work was completed while JAS was a visitor to the Isaac Newton Institute in Cambridge; their support is greatly appreciated. This work was supported by NSF grants AST 93/18617 and AST 96/17088 and by NASA Theory grant NAG 5-2803. Conversations with David Merritt and Stacy McGaugh have been very useful. Ray Carlberg, Jeremy



Goodman, Martin Haehnelt, Jim Pringle, Scott Tremaine and the referee, Alar Toomre, made helpful comments on the manuscript.

## REFERENCES

- Athanassoula, E. 1992, MNRAS, **259**, 345
- Athanassoula, E. 1996, in *Barred Galaxies*, IAU Colloq. 157, ed. R. Buta, D. A. Crocker, & B. G. Elmegreen (ASP Conf series 91), 309
- Athanassoula, E., Bosma, A. & Papaioannou, S. 1987, A&A, **179**, 23
- Bahcall, J. N. & Casertano, S. 1986, ApJ, **308**, 347.
- Barnes, J. E. 1992, ApJ, **393**, 484
- Barnes, J. E. & Hernquist, L. E., 1991, ApJ, **370**, L65
- Barnes, J. & White, S. D. M. 1984, MNRAS, **211**, 753.
- Becklin, E. E. & Neugebauer, G. 1968, ApJ, **151**, 145.
- Binney, J. & Tremaine, S. 1987, *Galactic Dynamics*, (Princeton: Princeton University Press)
- Blitz, L., Binney, J., Lo, K. Y., Bally, J. & Ho, P. T. P. 1993, Nature, **361**, 417
- Blumenthal, G. R., Faber, S. M., Flores, R. & Primack, J. R. 1986, ApJ, **301**, 27
- Bottema, R. 1993, A&A, **275**, 16
- Broeils, A. 1992, PhD Thesis, Groningen University
- Buchhorn, M. 1992. PhD Thesis, Australian National University
- Buta, R. & Crocker, D. A. 1993, AJ, **105**, 1344
- Carlberg, R. G. & Freedman, W. L. 1985, ApJ, **298**, 486
- Casertano, S. & van Albada, T. S., 1990, In *Baryonic Dark Matter*, eds D. Lynden-Bell & G. Gilmore (Dordrecht: Kluwer) p 159
- Casertano, S. & van Gorkom, J. H., 1991, AJ, **101**, 1231

- Chokshi, A. & Turner, E. L., 1992, MNRAS, **259**, 421
- Christodoulou, D. M., Shlosman, I. & Tohline, J. E. 1995, ApJ, **443**, 551
- Contopoulos, G. & Grosbøl, P., 1989, A&A Rev., **1**, 261
- Courteau, S. & Rix, H-W. 1997, astro-ph/9707290
- Dalcanton, J., Spergel, D. N. & Summers, J. J. 1997, ApJ, **482**, 659
- Debattista, V. P. & Sellwood, J. A. 1998, ApJ, **493**, L5
- de Blok, W. J. G., & McGaugh, S. S. 1996, ApJ, **469**, L89
- de Vaucouleurs, G. 1964, in *The Galaxy and the Magellanic Clouds* IAU Symposium **20**, eds. F. J. Kerr & A. W. Rodgers (Australian Academy of Science, Sidney) p 195
- Dubinski, J. & Carlberg, R. G. 1991, ApJ, **378**, 496
- Efstathiou, G., Lake, G. & Negroponte, J. 1982, MNRAS, **199**, 1069
- Eisenstein, D. J. & Loeb, A. 1995, ApJ, **443**, 11
- Elmegreen, D. M., Elmegreen, B. G. & Bellin, A. D. 1990, ApJ, **364**, 415.
- Englmaier, P. & Gerhard, O. E. 1998, in preparation
- Evans, N. W. & Read, J. C. A. 1998, MNRAS, to appear
- Fall, S. M. & Efstathiou, G. 1980, MNRAS, **193**, 189
- Freeman, K. C. 1992, in *Physis of Nearby Galaxies, Nature or Nurture?*, ed. T. X. Thuan et al. (Gif-sur-Yvette: Editions Frontières), p 201
- Friedli, D. & Benz, W. 1993, A&A, **268**, 65
- Gunn, J. E. 1982. In *Astrophysical Cosmology* p 233 eds H. A. Brück, G. V. Coyne & M. S. Longair (Vatican City: Pontificia Academia Scientiarum)
- Haehnelt, M. G. & Rees, M. 1993, MNRAS, **263**, 168

- Hasan, H. & Norman, C. 1990, *ApJ*, **361**, 69
- Helfer, T. T. & Blitz, L., 1995, *ApJ*, **450**, 90
- Heller, C. H. & Shlosman, I. 1994, *ApJ*, **424**, 84
- Jablonka, J. & Arimoto, N., 1994, *A&A*, **255**, 63
- Kalnajs, A. J. 1983, in *Internal Kinematics and Dynamics of Galaxies*, IAU Symp. 100, ed E. Athanassoula (Dordrecht: Reidel) p 87
- Kent, S. M. 1986, *AJ*, **91**, 1301
- Knapen, J. H., Beckman, J. E., Heller, C. H., Shlosman, I. & de Jong, R. S. 1995, *ApJ*, **454**, 623
- Kormendy, J. & McClure, R. D. 1993, *AJ*, **105**, 1793
- Kravtsov, A. V., Klypin, A. A., Bullock, J. S. & Primack, J. R. 1998, *ApJ*, submitted – astro-ph/9708176
- Kuijken, K. 1995, in *Stellar Populations*, IAU Symposium **164**, eds P. C. van der Kruit & G. Gilmore (Dordrecht: Kluwer), 195
- Lacey, C. G. & Ostriker, J. P. 1985, *ApJ*, **299**, 633
- Lehnert, M. D., Heckman, T. M., Chambers, K. C. & Miley, G. K. 1992, *ApJ*, **393**, 68
- Lynden-Bell, D. 1969, *Nature*, **223**, 690
- Magorrian, J. et al. 1998, *AJ*, **115**, 2285
- Merritt, D. & Quinlan, G. 1998, *ApJ*, **498**, 625
- Mestel, L. 1963, *MNRAS*, **126**, 553.
- Mo, H. J., Mao, S. & White, S. D. M. 1998, *MNRAS*, **295**, 319
- Navarro, J. F. 1997, in *Dark and Visible Matter in Galaxies*, ed. M. Persic & P. Salucci (San Francisco: ASP Conf. Ser. 117), 404

- Navarro, J. F. & Benz, M., 1991, ApJ, **380**, 320
- Navarro, J. F., Frenk, C. S. & White, S. D. M. 1996, ApJ, **462**, 563
- Navarro, J. F. & Steinmetz, M., 1997, ApJ, **478**, 13
- Noguchi, M. 1987, MNRAS, **228**, 635.
- Noguchi, M. 1988, A&A, **203**, 259
- Norman, C. A., Sellwood, J. A., & Hasan, H. 1996, ApJ, **462**, 114
- Ostriker, J. P., & Peebles, P. J. E. 1973, ApJ, **186**, 467
- Padovani, P., Burg, R. & Edelson, R. A. 1990, ApJ, **353**, 438
- Palunas, P. & Williams, T. B. 1998, AJ, submitted
- Pfenniger, D. 1991, in *Dynamics of Disc Galaxies*, ed. B. Sundelius (University of Gothenburg), p 191
- Pfenniger, D., Combes, F. & Martinet, L. 1994, A&A, **285**, 79
- Prendergast, K. H. 1983, in *Internal Kinematics and Dynamics of Galaxies*, IAU Symp. 100, ed E. Athanassoula (Dordrecht: Reidel) p 215
- Quillen, A. C., Frogel, J. A., Kenney, J. D. P., Pogge, R. W. & Depoy, D. L. 1995, ApJ, **441**, 549
- Rees, M. J., 1997, astro-ph/9701161
- Rubin, V. C., Ford, W. K., & Thonnard, N. 1980, ApJ, **238**, 471
- Rubin, V. C., Kenney, J. D. P. & Young, J. S., 1997, AJ, **113**, 1250
- Ryden, B. S. & Gunn, J. E. 1987, ApJ, **318**, 15
- Sackett, P. D. 1997, ApJ, **483**, 103
- Schmidt, M., Schneider, D. P. & Gunn, J. E. 1995, AJ, **110**, 68

- Sellwood, J. A., 1981, *A&A*, **99**, 362
- Sellwood, J. A. 1989, *MNRAS*, **238**, 115
- Sellwood, J. A. 1998, astro-ph/9711335
- Sellwood J. A. & Carlberg R. G. 1984, *ApJ*, **282**, 61
- Sellwood J. A. & Valluri, M. 1997, *MNRAS*, **287**, 124
- Sellwood, J. A. & Wilkinson, A. 1993, *Rep. Prog. Phys.*, **56**, 173
- Shaver, P. A., Wall, J. V., Kellerman, K. I., Jackson, C. A. & Hawkins, M. R. S. 1996, *Nature*, **384**, 439
- Shlosman, I., Begelman, M. C. & Frank, J., 1990, *Nature*, **345**, 679
- Silk, J. & Rees, M. J., 1998, astro-ph/9801013
- Small, T. A. & Blandford, R. D. 1992, *MNRAS*, **259**, 725
- Taylor, G. L., Dunlop, J. S., Hughes, D. H. & Robson, E. I. 1996, *MNRAS*, **283**, 930
- Toomre, A. 1981, in *Structure and Evolution of Normal Galaxies*, eds S. M. Fall & D. Lynden-Bell (Cambridge: Cambridge University Press), 111
- Toomre, A. 1990, in *Dynamics & Interactions of Galaxies*, ed. R. Wielen, (Berlin, Heidelberg: Springer-Verlag), 292
- van Albada, T. S. & Sancisi, R. 1986, *Phil Trans London A*, **320**, 447
- van der Kruit, P. C. 1987, *A&A*, **173**, 59
- van der Kruit, P. C. 1995, in *Stellar Populations*, IAU Symposium **164**, eds P. C. van der Kruit & G. Gilmore (Dordrecht: Kluwer), 205
- Villumsen, J. V. & Gunn, J. E. 1987, unpublished
- Weinberg, M. D. 1985, *MNRAS*, **213**, 451
- Weiner, B., Sellwood, J. A., Williams, T. B. & van Gorkom, J. 1998, in preparation

White, S. D. M. & Rees, M. J. 1978, *MNRAS*, **183**, 341

Worthey, G. 1994, *ApJS*, **95**, 107

Zang, T. A. 1976, PhD Thesis, MIT

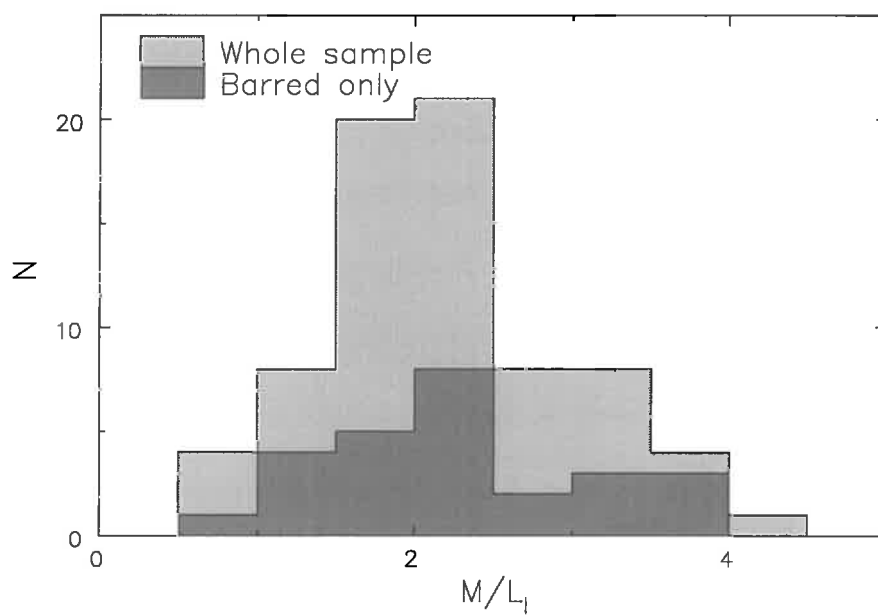


Fig. 1.—  $M/L_I$  ratios obtained by Palunas & Williams (1998) for the disk components in their maximum disk fits. Their values have been adjusted for  $H_0 = 60 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .



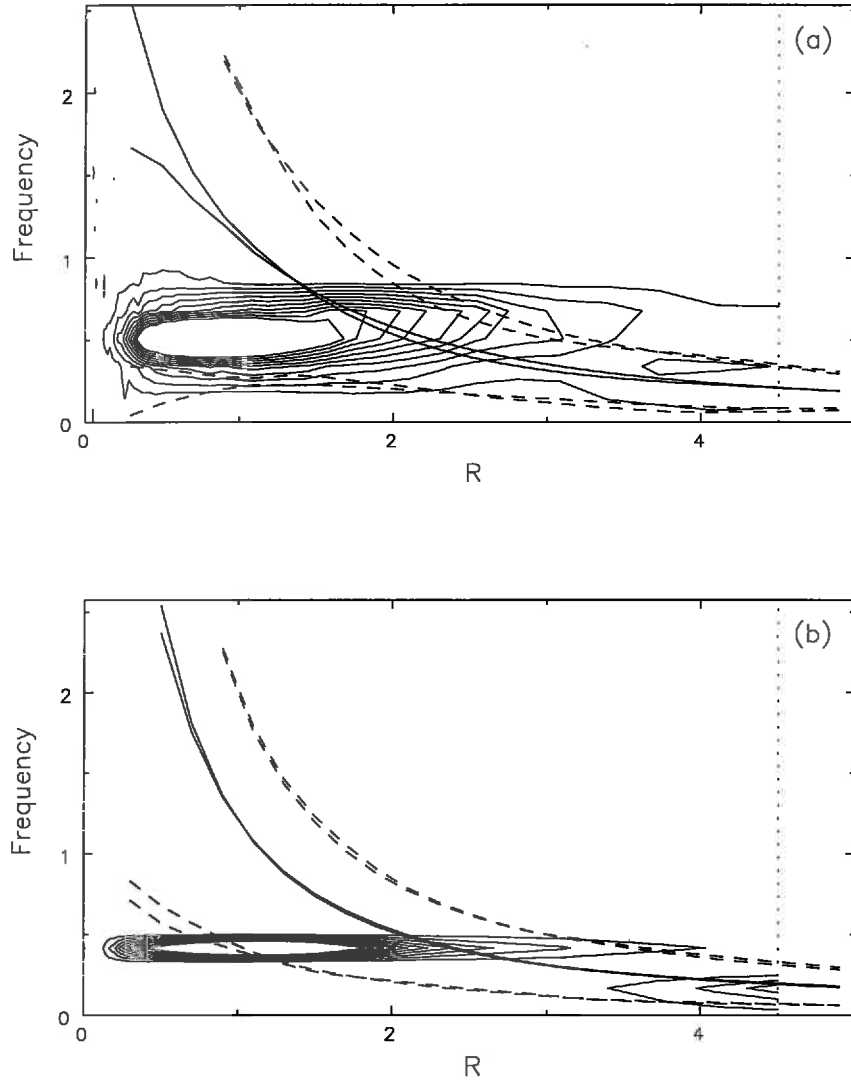


Fig. 2.— Contours of power in bi-symmetric density perturbations as a function of radius and frequency over two different time intervals in model 1. The upper plot is over a short initial period ( $0 \leq t \leq 40$ ) during which the bar forms, the lower plot is from a later time interval ( $95 \leq t \leq 170$ ) as the central mass reaches its final mass. The full-drawn lines show curves of the circular angular frequency  $\Omega$  and the dashed curves mark  $\Omega \pm \kappa/2$ . In both plots, these curves are determined from the mean central attraction in the model at the beginning and end of the adopted time range.

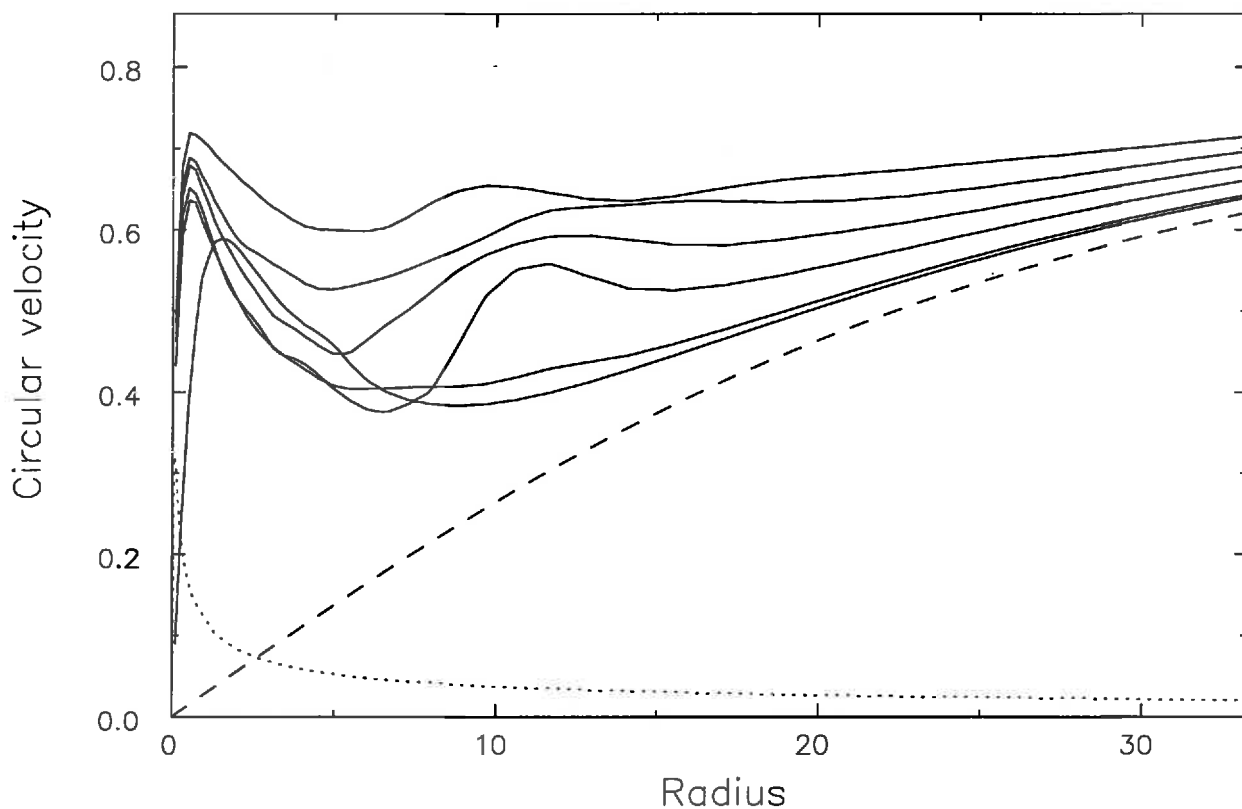


Fig. 3.— The rotation curve at the six times 0(192)960 (full-drawn lines); the circular velocity at both  $R \sim 1$  and  $R \sim 10$  rises monotonically over time. The dashed curve is the fixed halo contribution and the dotted curve shows the contribution from the central mass only, which is absent at  $t = 0$  but the same for all other times shown.

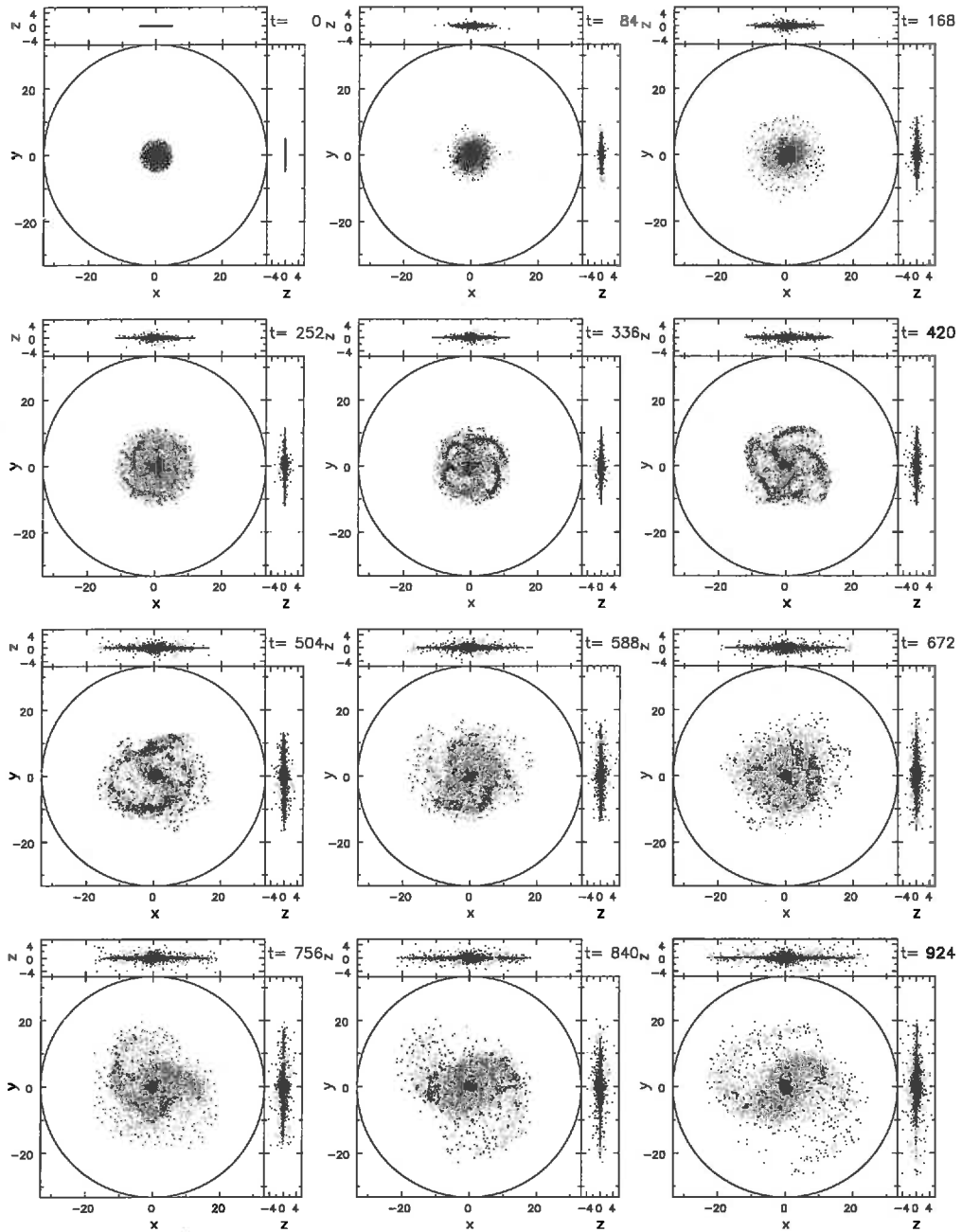


Fig. 4.— (a) Snapshots of model 1 at equally spaced times. The number of particles in the simulation increases after time 160, but each plot shows a random selection of about 5000. Particles are added in the range  $8 \leq R \leq 12$  only, but are spread radially by the strong spiral patterns. Notice that this almost fully self-gravitating disk has no bar in the second half of the evolution.

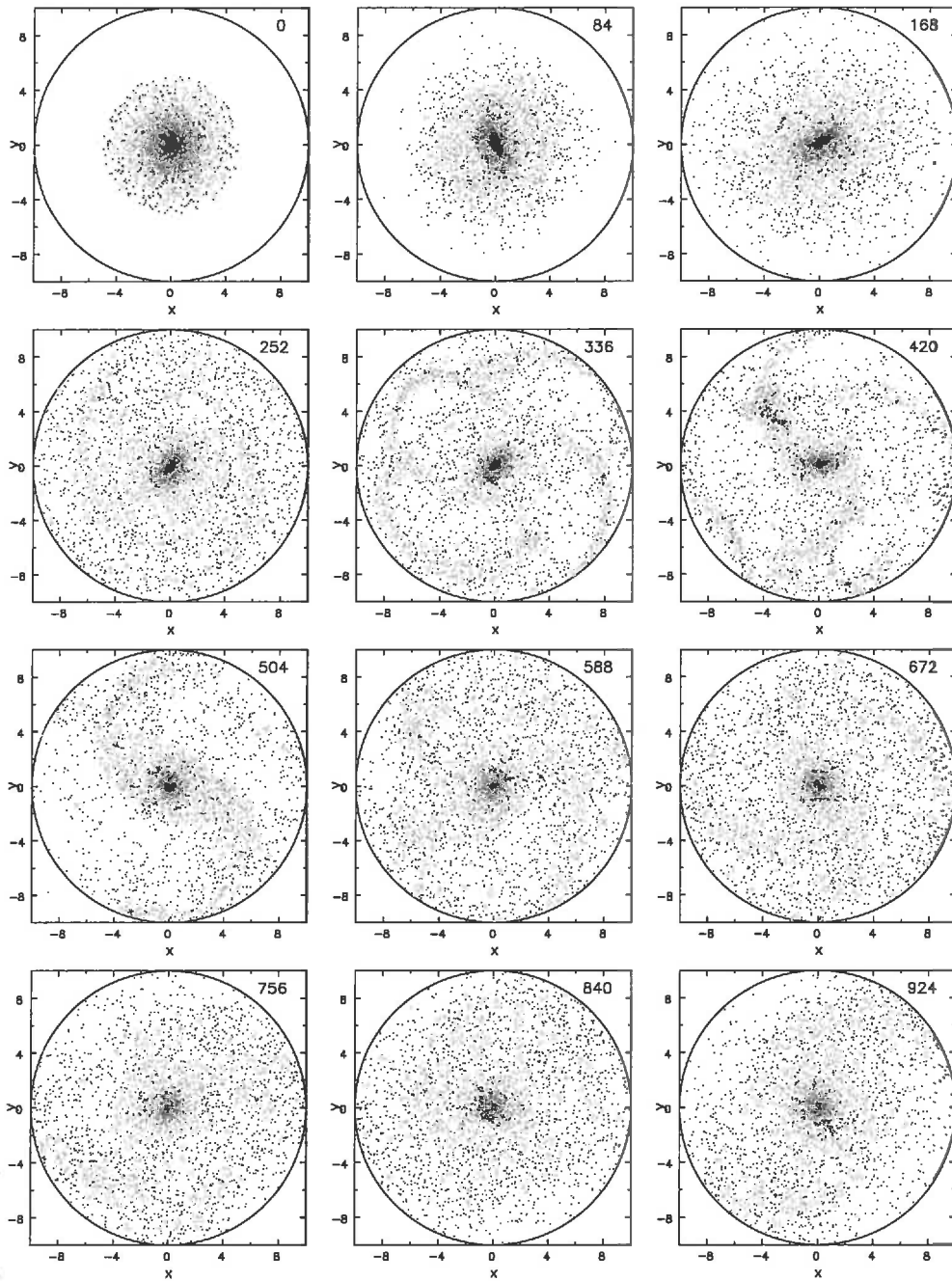


Fig. 4.— (b) Close-up views of the inner region of the model shown in (a).

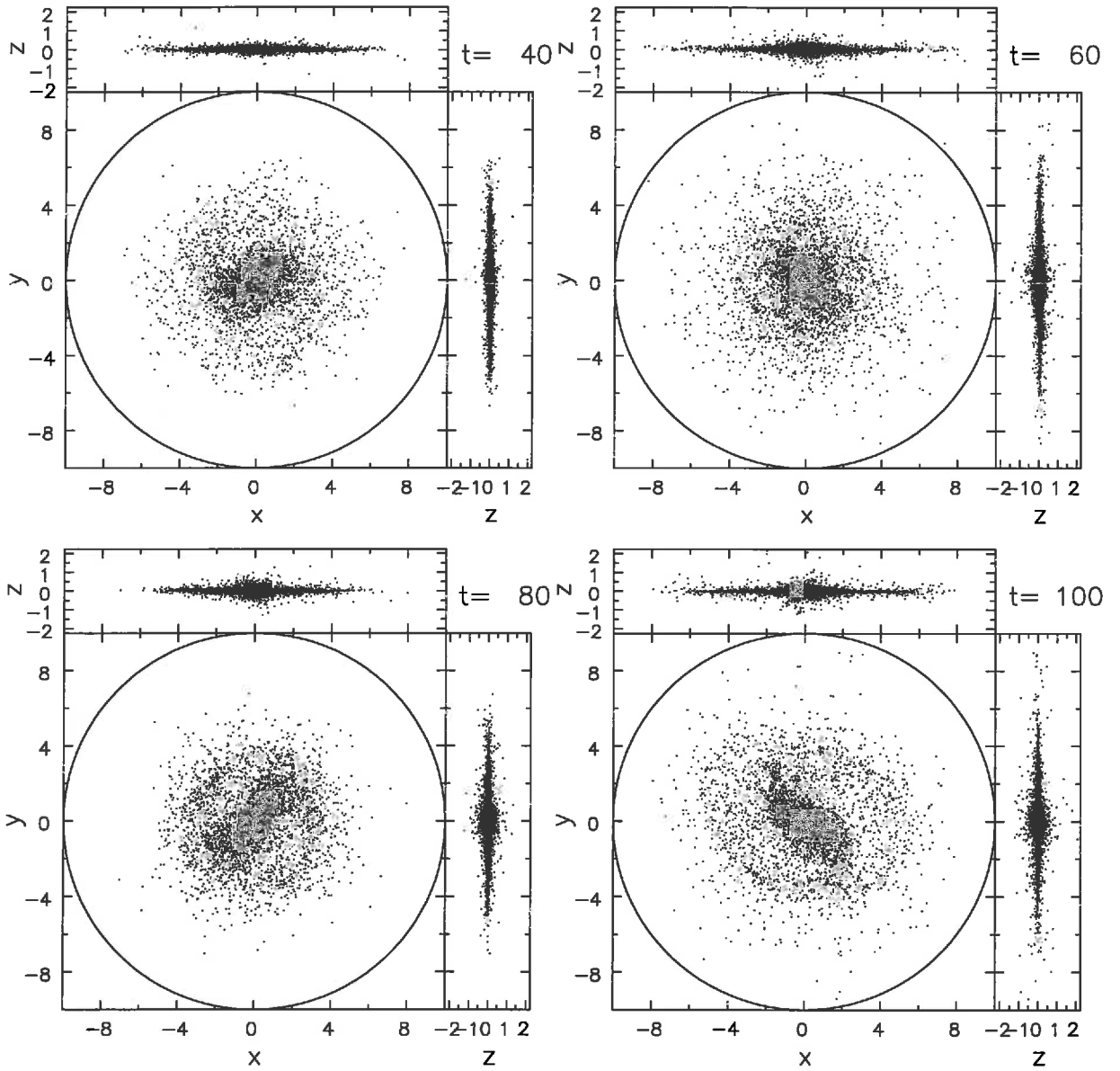


Fig. 5.— Snapshots of model 2 in which particles are added at much smaller radii than in model 1. This low angular momentum material causes the bar to gain strength, unlike in Figure 4.

Table 1. Summary of the two models

Quantity	Model 1	Model 2	unit
Numerical Parameters			
Initial number of particles ...	$4 \times 10^4$	$4 \times 10^4$	
Grid size ( $R, \phi, z$ ) .....	$72 \times 66 \times 375$	$65 \times 64 \times 225$	
Vertical plane spacing .....	0.03	0.02	$a$
Grid boundaries ( $R, z$ ) .....	(33.6, $\pm 5.61$ )	(20.1, $\pm 2.24$ )	$a$
Softening length .....	0.05	0.05	$a$
Time step .....	0.04	0.02	$(a^3/GM)^{1/2}$
Initial Disk			
Toomre $Q$ .....	1.5	1.5	
RMS vertical thickness .....	0.05	0.05	$a$
Truncation radius .....	5	5	$a$
Accretion rule			
Time accretion starts .....	160	40	$(a^3/GM)^{1/2}$
Particles added per time step	8	4	
Accretion rule .....	uniform in $R$	Gaussian in $J$	
	$8 \leq R \leq 12$	$\bar{J} = 1 + 0.01t$	$\sigma = 0.5 a, (GMa)^{1/2}$
Fixed halo			
$V_0$ .....	0.7	0.7	$(GM/a)^{1/2}$
Core radius .....	30	30	$a$
Central Mass			
Core radius .....	0.05	0.05	$a$
Radial range for $\alpha_2/\alpha_0$ .....	$1 \leq R \leq 2$	$1 \leq R \leq 2$	$a$
Mass rises when $\alpha_2/\alpha_0 >$ ....	0.4	0.4	
$dM/dt$ .....	$2.5 \times 10^{-4}$	$2.5 \times 10^{-3}$	$(GM^3/a^3)^{1/2}$
Period of growth .....	$24 \leq t \leq 80$	$24 \leq t \leq 30$	$(a^3/GM)^{1/2}$
Final mass .....	0.014	0.017	$M$

## Recent Newton Institute Preprints

- NI97028-NQF **CM Hull**  
*Gravitational duality, branes and charges*  
hep-th/9705162; Nucl.Phys. B509 (1998) 216-251
- NI97029-NQF **M Abou Zeid and CM Hull**  
*Intrinsic geometry of D-branes*  
hep-th/9704021; Phys.Lett. B404 (1997) 264-270
- NI97030-NQF **CP Bachas, MR Douglas and MB Green**  
*Anomalous creation of branes*  
hep-th/9705074
- NI97031-RAG **M Broué, G Malle and J Michel**  
*Complex reflection groups, braid groups, Hecke algebras*
- NI97032-NQF **D Zwanziger**  
*Renormalization in the Coulomb gauge and order parameter for confinement in QCD*
- NI97033-NQF **E Shuryak and A Zhitnisky**  
*The gluon/charm content of the  $\eta'$  meson and instantons*  
hep-ph/9706316; Phys.Rev. D57 (1998) 2001-2004
- NI97035-RAG **K Magaard and G Malle**  
*Irreducibility of alternating and symmetric squares*
- NI97036-STA **N Linden and S Popescu**  
*On multi-particle entanglement*
- NI97037-NNM **M Studeny and RR Bouckaert**  
*On chain graph models for description of conditional independence structures*
- NI97038-RAG **M Geck and G Malle**  
*On special pieces in the unipotent variety*
- NI97039-NNM **SP Luttrell**  
*A unified theory of density models and auto-encoders*  
DERA report DERA/CIS/CIS5/651/FUN/STIT/5-4 31 October 1997
- NI97040-NNM **CKI Williams and D Barber**  
*Bayesian Classification with Gaussian Processes*
- NI97041-NNM **TS Richardson**  
*Chain graphs and symmetric associations*
- NI97042-NNM **A Roverato and J Whittaker**  
*An importance sampler for graphical Gaussian model inference*
- NI97043-DQC **MR Haggerty, JB Delos, N Spellmeyer et al**  
*Extracting classical trajectories from atomic spectra*
- NI97044-DQC **S Zelditch**  
*Large level spacings for quantum maps in genus zero*
- NI97045-DQC **U Smilansky**  
*Semiclassical quantization of maps and spectral correlations*
- NI97046-DQC **IY Goldscheid and BA Khoruzhenko**  
*Distribution of Eigenvalues in non-Hermitian Anderson models*  
Phys. Rev. Lett. 80 (1998) No.13, 2897-2900
- NI97047-DQC **G Casati, G Maspero and DL Shepelyansky**  
*Quantum fractal Eigenstates*
- NI98001-STA **N Linden and S Popescu**  
*Non-local properties of multi-particle density matrices*
- NI98002-AMG **J-L Colliot-Thélène**  
*Un principe local-global pour les zéro-cycles sur les surfaces fibrés en coniques au-dessus d'une courbe de genre quelconque*
- NI98003-AMG **RGE Pinch and HPF Swinnerton-Dyer**  
*Arithmetic of diagonal quartic surfaces, II*

- NI98004-AMG **DR Heath-Brown**  
*The solubility of diagonal cubic diophantine equations*
- NI98005-AMG **B Poonen and M Stoll**  
*The Cassels-Tate pairing on polarized Abelian varieties*
- NI98006-AMG **P Parimala and V Suresh**  
*Isotropy of quadratic forms over function fields of curves over  $p$ -adic fields*
- NI98007-AMG **E Peyre**  
*Application of motivic complexes to negligible classes*
- NI98008-AMG **E Peyre**  
*Torseurs universels et méthode du cercle*
- NI98009-RAG **JA Green**  
*Discrete series characters for  $GL(n, q)$*
- NI98010-DQC **K Zyczkowski**  
*On the volume of the set of mixed entangled states*
- NI98011-DQC **K Zyczkowski**  
*Monge distance between quantum states*
- NI98012-DAD **JA Sellwood, RW Nelson and S Tremaine**  
*Resonant thickening of disks by small satellite galaxies*
- NI98013-DAD **GI Ogilvie and SH Lubow**  
*The effect of an isothermal atmosphere on the propagation of three-dimensional waves in a thermally stratified accretion disk*
- NI98014-DAD **JA Sellwood and SA Balbus**  
*Differential rotation and turbulence in extended  $H I$  disks*
- NI98015-DAD **AM Fridman and OV Khoruzhii**  
*On nonlinear dynamics of 3D astrophysical disks*
- NI98016-DQC **RE Prange, R Narevich and O Zaitsev**  
*Quasiclassical surface of section perturbation theory*
- NI98017-DQC **A Sedrakyan**  
*Edge excitations of an incompressible fermionic liquid in a disorder magnetic field*
- NI98018-DAD **CF Gammie**  
*Accretion disk turbulence*
- NI98019-DAD **R Popham and CF Gammie**  
*Advection dominated accretion flows in the Kerr metric: II. Steady state global solutions*
- NI98020-DAD **CF Gammie and R Narayan**  
*What is the accretion rate in NGC 4258?*
- NI98021-DAD **CF Gammie**  
*Photon bubbles in accretion disks*
- NI98022-DAD **EC Ostriker, CF Gammie and JM Stone**  
*Kinetic and structural evolution of self-gravitating, magnetized clouds: 2.5-dimensional simulations of decaying turbulence*
- NI98023-DAD **JA Sellwood and EM Moore**  
*On the formation of disk galaxies and massive central objects*
- NI98024-STA **VA Vladimirov, HK Moffatt and KI Ilin**  
*On general transformations & variational principles for the magnetohydrodynamics of ideal fluids. Part IV. Generalized isovorticity principle for three-dimensional flows*
- NI98025-BFG **M Steel**  
*Sufficient conditions for two tree reconstruction techniques to succeed on sufficiently long sequences*
- NI98026-BFG **M Steel**  
*The emergence of a self-catalysing structure in abstract origin-of-life models*