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SECULAR EVOLUTION IN DISK GALAXIES: THE GROWTH OF PSEUDOBULGES AND PROBLEMS FOR COLD DARK MATTER GALAXY FORMATION

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RESUMEN

Reseñamos la evolucón secular interna en discos de galaxias, el proceso fundamental mediante el cual evolucionan los discos aislados, concentrándonos en las características de densidad central que semejan bulbos clásicos construidos por fusión pero que se han formado lentamente a partir de discos de gas. A éstos los llamamos seudobulbos. Como una prueba de existencia, reseñamos como las las barras reacomodan el disco del gas en discos externos, discos internos y gas vertido al centro. En simulaciones este gas alcanza altas densidades, mientras que las observaciones de muchas galaxias SB y ovoides muestran concentraciones centrales de gas. ¿Cómo podemos distinguir los procesos seculares que formaron los centros densosde los bulbos formados por fusión? Las observaciones muestran que los seudobulbos retienen sus orígenes de discos. Tienen una o más características: (1) forma más planas, (2) mayor cociente de velocidades ordenadas a velocidades al azar, (3) menor velocidad de dispersión, (4) barra en el núcleo o estructura espiral, (5) estructura de caja, al verse de lado, (6) perfil de brillo casi exponencial, y (7) brote de formación estelar. Estas características ocurren preferentemente en galaxias barradas y ovales en las cuales la evolución secular debió de haber sido rápida. Los ejemplos más nítidos de seudobulbos son reconocibles. Tanto las observaciones como la teoría contribuyen a un nuevo esquema de evolución que complementa la acumulación jerŕquica y la fusión.
Sin embargo, se agudiza un problema importante en la formación de galaxias con materia oscura. ¿Cómo puede la acumulación jerárquica producir tantas galaxias simples de disco sin evidencia de bulbos formados por fusión?

ABSTRACT

We review internal secular evolution in galaxy disks – the fundamental process by which isolated disks evolve. We concentrate on the buildup of dense central features that look like classical, merger-built bulges but that were made slowly out of disk gas. We call these pseudobulges. As an existence proof, we review how bars rearrange disk gas into outer rings, inner rings, and gas dumped into the center. In simulations, this gas reaches high densities, and in the observations, many SB and oval galaxies show central concentrations of gas. Associated star formation rates imply plausible pseudobulge growth times of a few billion years.
If secular processes built dense centers that masquerade as bulges, can we distinguish them from merger-built bulges? Observations show that pseudobulges retain a memory of their disky origin. They have one or more characteristics of disks: (1) flatter shapes than those of classical bulges, (2) larger ratios of ordered to random velocities, (3) smaller velocity dispersions, (4) nuclear bars or spiral structure, (5) boxy structure when seen edge-on, (6) nearly exponential brightness profiles, and (7) starbursts. These features occur preferentially in barred and oval galaxies in which secular evolution should be rapid. So the cleanest examples of pseudobulges are recognizable. Thus observations and theory contribute to a new picture of galaxy evolution that complements hierarchical clustering and merging.
However, an important problem with cold dark matter galaxy formation gets more acute. How can hierarchical clustering produce so many pure disk galaxies with no evidence for merger-built bulges?

Key Words: **GALAXIES: EVOLUTION — GALAXIES: FORMATION — GALAXIES: KINEMATICS AND DYNAMICS — GALAXIES: NUCLEI**

1. INTRODUCTION

Galactic evolution is in transition from the early Universe dominated by hierarchical clustering to a future dominated by internal secular processes. These result from interactions involving collective phenomena such as bars, oval disks, spiral structure, and triaxial dark halos. This paper summarizes and updates reviews by Kormendy (1993) and especially by Kormendy & Kennicutt (2004, hereafter KK04).

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2. THE FUNDAMENTAL WAY THAT DISKS EVOLVE IS BY SPREADING

A general principle[2] of the evolution of self-gravitating systems is that it is energetically favorable to spread – to shrink the inner parts by expanding the outer parts. The easiest way to see this depends on whether the system is dominated by rotation or by random motions.

2.1. *If Dynamical Support Is By Random Motions*

Then the argument (Lynden-Bell & Wood 1968; Binney & Tremaine 1987) is based on the fundamental point that the specific heat of a self-gravitating system is negative. Consider an equilibrium system of N particles of mass m, radius r, and three-dimensional velocity dispersion v. The virial theorem says that $2\,\mathrm{KE} + \mathrm{PE} = 0$, where the kinetic energy $\mathrm{KE} = Nmv^2/2$ and the potential energy $\mathrm{PE} = -G(Nm)^2/r$ define v and r. The total energy of a bound system, $E \equiv \mathrm{KE} + \mathrm{PE} = -\mathrm{KE}$, is negative. But temperature T corresponds to internal velocity as $mv^2/2 = 3kT/2$. So the specific heat $C \equiv dE/dT \propto d(-Nmv^2/2)/d(v^2)$ is also negative. In the above, G is the gravitational constant and k is Boltzmann's constant.

The system is supported by heat, so evolution is by heat transport. If the center of the system is hotter than the periphery, then heat tends to flow outward. The inner parts shrink and get still hotter. This promotes further heat flow. The outer parts receive heat; they expand and cool. Whether the system evolves on an interesting timescale depends on whether there is an effective heat-transport mechanism. For example, many globular clusters evolve quickly by two-body relaxation and undergo core collapse. Giant elliptical galaxies – which otherwise would evolve similarly – cannot do so because their relaxation times are much longer than the age of the Universe.

2.2. *If Dynamical Support Is By Rotation*

Tremaine (1989) provides a transparent summary of an argument due to Lynden-Bell & Kalnajs (1972) and to Lynden-Bell & Pringle (1974). A disk is supported by rotation, so evolution is by angular momentum transport. The "goal" is to minimize the total energy at fixed total angular momentum. A rotationally supported ring at radius r in a fixed potential $\Phi(r)$ has specific energy $E(r)$ and specific angular momentum $L(r)$ given by

$$E(r) = \frac{r}{2}\frac{d\Phi}{dr} + \Phi \quad \text{and} \quad L(r) = \left(r^3\,\frac{d\Phi}{dr}\right)^{1/2} .$$

[2]Exceptions exist but are rare and somewhat contrived.

Then $dE/dL = \Omega(r)$, where $\Omega = (r^{-1}d\Phi/dr)^{1/2}$ is the angular speed of rotation. Disks spread when a unit mass at radius r_2 moves outward by acquiring angular momentum dL from a unit mass at radius $r_1 < r_2$. Is this energetically favorable? The answer is yes. The net change in energy,

$$\begin{aligned} dE = dE_1 + dE_2 \;\; &= \;\; \left[-\left(\frac{dE}{dL}\right)_1 + \left(\frac{dE}{dL}\right)_2\right] dL\,, \\ &= \;\; \left[-\Omega(r_1) + \Omega(r_2)\right] dL\,, \end{aligned}$$

is negative because $\Omega(r)$ usually decreases outward. "Thus disk spreading leads to a lower energy state. In general, disk spreading, outward angular momentum flow, and energy dissipation accompany one another in astrophysical disks" (Tremaine 1989).

2.3. *Self-Gravitating Systems Evolve By Spreading*

The consequences are very general. All of the following are caused by the same basic physics.

Globular and open clusters are supported by random motions, so they spread in three dimensions by outward energy transport. The mechanism is two-body relaxation, and the consequences are core collapse and the evaporation of the outer parts.

Stars are spherical systems supported by pressure. They spread in three dimensions by outward energy transport. The mechanisms are radiation or convection mediated by opacity. Punctuated by phases of stability when nuclear reactions replace the energy that is lost, stellar evolution consists of a series of core contractions and envelope expansions. One result is red (super)giants.

Protostars are spherical systems coupled to circumstellar disks. The spreading is complicated. The star shrinks in three dimensions; the inner disk shrinks in two dimensions. Jets that look one-dimensional but that really are three-dimensional carry away angular momentum (Shu et al. 1994, 1995). The mechanism involves magnetic fields wound up by differential rotation. Coupled to the outer circumstellar disk, they cause it to expand.

Protoplanetary disks are supported by rotation; they spread in two dimensions by outward angular momentum transport. Dynamical friction produces, for example, hot Jupiters and colder Neptunes.

Galactic disks are supported by rotation. Exceptions are possible, but in general, they want to spread in two dimensions by outward angular momentum transport. Efficient driving mechanisms are provided by bars and globally oval disks. Like all of the above, the evolution is secular – it is slow

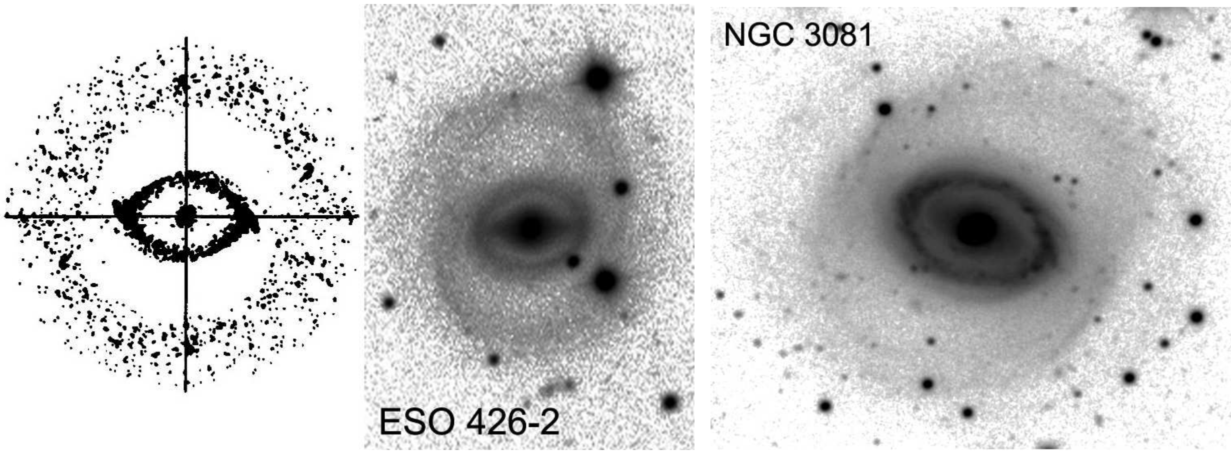

Fig. 1. Products of secular evolution: (left) Gas particle distribution at the end of a sticky-particle simulation of the evolution of gas in a rotating bar potential that is horizontal but not shown (Simkin, Su, & Schwarz 1980). After 7 bar rotations, gas has collected into an outer ring, an inner ring around the end of the bar, and a dense central concentration. Similar features are seen in barred galaxies such as ESO 426-2 (Buta & Crocker 1991) and NGC 3081 (Buta, Corwin, & Odewahn 2005). This figure is adapted from Kormendy & Kennicutt (2004).

compared to the collapse time of the disk. Bar-driven secular evolution is the subject of this paper.

3. HOW BARS REARRANGE DISKS

Many papers review simulations of bar-driven internal evolution (e. g., Kormendy 1982a, 1993; Athanassoula 1992; Sellwood & Wilkinson 1993; Buta & Combes 1996; KK04). Interestingly, simple sticky-particle simulations reproduce the structure of barred galaxies better than hydrodynamic simulations that include more detailed physics, although the latter reveal important aspects of the evolution that the former cannot see. Generic results are illustrated in Figure 1. Disk gas is rearranged into an "outer ring" at $\sim$ 2.2 bar radii, an "inner ring" that encircles the end of the bar, and a dense central concentration of gas. As the gas density increases, star formation is likely, and indeed, the features produced in gas closely resemble the outer rings, inner rings, and (it will turn out) pseudobulges observed in stars in disk galaxies (see the figure).

Morphological evidence consistent with the above interpretation includes ring shapes and orientations. Inner rings typically have axial ratios of $b/a \simeq 0.85$ and are oriented parallel to the bar (Athanassoula et al. 1982; Buta & Combes 1996). Outer rings have similar shapes and are oriented either parallel to or perpendicular to the bar (Kormendy 1979; Simkin et al. 1980; Athanassoula et al. 1982; Buta & Combes 1996). This is also consistent with the shapes of closed gas orbits if – as expected – bars typically end just inside corotation and if outer rings form just inside or just outside outer Lindblad resonance, respectively (see the above papers). Moreover, in galaxies of intermediate Hubble types, in which bars are red and made of old stars while disks are blue and dominated by young stars, the rings are also blue and full of young stars. Outer rings also generally contain gas and young stars, even in (R)SB0 galaxies. These points are illustrated in KK04.

Rings are useful partly because they provide clean diagnostics of the evolution, but they contain only a small fraction of the mass of the galaxy. A bigger and ultimately more important effect of the evolution results from the large amount of gas that is driven toward the center by tidal torques (e. g., Athanassoula 1992). In the simulations, it builds up to very high densities, often in rings (see KK04 for a review). Since star formation rate density $\Sigma_{\rm SFR}$ increases rapidly with gas density $\Sigma_{\rm gas}$, $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$ (Kennicutt 1998a, b), high star formation rates are expected. And indeed, they are observed. KK04 review extensive observations of nuclear starbursts, often in spectacular rings and often associated with bars and globally oval disks. They collect measurements of star formation rates in starbursting nuclear rings and show that these extend the above Kennicutt law from values seen in normal galactic disks to high star formation rates and $\Sigma_{\rm gas}$ values. With modest replenishment of the observed nuclear gas, they would build stellar densities that we observe in pseudobulges (see the next section) in typically 1 – 3 billion years. So the formation picture indicated by the simulations is plausibly connected via observed gas densities, star

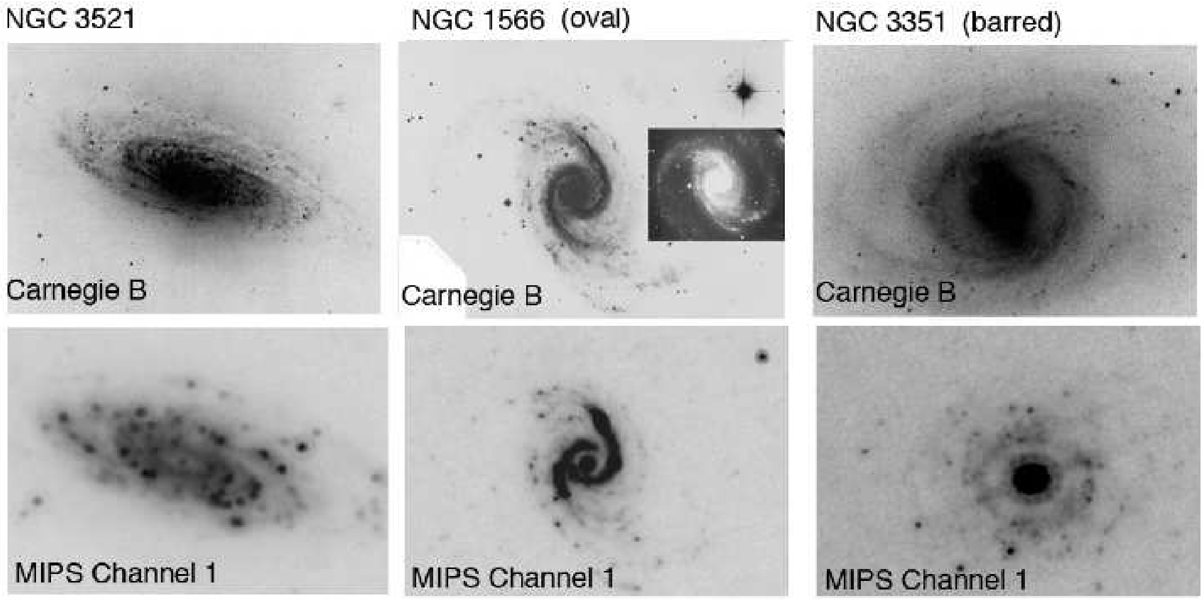

Fig. 2. Contrast the bright central 24 μm emission in NGC 1566, a globally oval galaxy, and in NGC 3351, a barred galaxy, with the faint central 24 μm emission in NGC 3521, a galaxy that is neither barred nor oval. The 24 μm MIPS images are from the Spitzer Space Observatory SINGS project (Kennicutt et al. 2003), while the comparison optical images are from the Carnegie Atlas of Galaxies (Sandage & Bedke 1994).

formation rates, and reasonable timescales with the disky bulges discussed in the next section.

Here, we illustrate the above picture with Spitzer Space Observatory images (Figure 2) of prototypical galaxies that are neither barred nor oval (NGC 3521, left), globally oval (NGC 1566, center), and barred (NGC 3351, right).

Ovals can be recognized kinematically (Bosma 1981) and photometrically (Kormendy & Norman 1979; Kormendy 1979, 1982a; KK04). NGC 1566 has the photometric signature of a strong oval: it shows two distinct "shelves" in the brightness distribution with different axial ratios and position angles. The high-surface-brightness, inner shelf contains the most prominent spiral structure and is elongated N–S (vertically in Figure 2), while the outer shelf is much lower in surface brightness (see the inset) and is elongated horizontally in the figure. Both cannot be round if they are coplanar, and studies of H I warps in edge-on galaxies show that the alternative – warped disks – do not generally occur at such high surface brightnesses (Bosma 1981). Each nested oval generally has $b/a \sim 0.85$ (see the above papers). Ovals are important because they are easily nonaxisymmetric enough to drive secular evolution just like that in barred galaxies.

The three galaxies shown in Figure 2 support the evolution picture discussed above. The two galaxies that have prominent disk nonaxisymmetries also are very bright near the center in the Spitzer MIPS 24 μm images. These are sensitive to warm dust that reradiates light from young stars. That is, they indicate high star formation rates. In contrast, NGC 3521, which has neither a bar nor an oval disk, shows little 24 μm emission near the center. Three galaxies do not constitute a statistical sample, but optical observations suggest that the above behavior is typical (KK04). Spitzer will provide quantitative checks of the statistics of such observations.

4. PSEUDOBULGE PROPERTIES

Kormendy (1982a, b) suggested that secular inward gas transport and star formation make disk-like "bulges". Combes & Sanders (1981) suggested that boxy bulges formed from bars that heated themselves in the axial direction. Pfenniger & Norman (1990) discuss both processes. A new dissipationless process – that bars thicken in the axial direction as they decay – is suggested by Klypin et al. (2005). These themes – dissipational and dissipationless, secular pseudobulge building – are widespread in the literature (see KK04 for review).

How can we tell whether a "bulge" formed by these processes? Fortunately, pseudobulges retain enough memory of their disky origin so that the best examples are recognizable. Structural features that indicate a disky origin are listed in KK04 and below. We also give a few examples and updates.

Any prescription must recognize that we expect a continuum from classical, merger-built bulges through objects with some E-like and some disk-like characteristics to pseudobulges built completely by secular processes. Uncertainties are inevitable when we deal with transition objects. Keeping these in mind, a list of pseudobulge characteristics includes:

1. The candidate pseudobulge is seen to be a disk in images: it has spiral structure or its ellipticity $\epsilon = 1 - b/a$ is similar to that of the outer disk.

   One example among many, NGC 1353, is shown in Figure 3. The images show, as Carollo et al. (1997, 1998) concluded, that the central structure in NGC 1353 is a disk with similar flattening and orientation as the outer disk. To make this quantitative, KK04 measured the surface brightness, ellipticity, and position angle profiles (plots in Figure 3). The apparent flattening at $2'' \lesssim r \lesssim 4''$ is the same as that of the main disk at large radii. The position angle is the same, too. So the part of the galaxy shown in the top-right panel really is a disk. The brightness profile shows that this nuclear disk is responsible for much of the central rise in surface brightness above the inward extrapolation of an exponential fitted to the outer disk. Presented only with the brightness profile or with the bottom two panels of images, we would identify the central rise in surface brightness as a bulge. Given Figure 3, we identify it as a pseudobulge.

2. It is or it contains a nuclear bar (in face-on galaxies). Bars are disk phenomena; they are fundamentally different from triaxial ellipticals.

3. It is box-shaped (in edge-on galaxies). Boxy bulges are believed to be the central parts of edge-on bars that heated themselves in the axial direction (see Sellwood & Wilkinson 1993 for a review). Again, bars are disk phenomena.

4. It has $n \simeq 1$ to 2 in a Sérsic (1968) function, $I(r) \propto e^{-K[(r/r_e)^{1/n}-1]}$, fit to the brightness profile. Here $n = 1$ for an exponential, $n = 4$ for an $r^{1/4}$ law, and $K(n)$ is chosen so that radius r_e contains half of the light in the Sérsic component. We do not understand pseudobulge or disk formation well enough to predict n, so a nearly exponential profile does not *prove* that a component is disk-like in the same way that high flattening or large $V_{\max}/\sigma$ (see 5) do. Instead, combining n with other pseudobulge indicators shows empirically that nearly exponential profiles are a characteristic of many pseudobulges (Andredakis & Sanders 1994; Andredakis, Peletier, & Balcells 1995; Courteau, de Jong, & Broeils 1996; Carollo et al. 2002; Balcells et al. 2003; MacArthur, Courteau, & Holtzman 2003; KK04). Again, NGC 1353 (Figure 3) is an example. KK04 decomposed the major-axis profile into an exponential outer disk plus a Sérsic function pseudobulge. The best fit gave $n = 1.3 \pm 0.3$.

   Whether this provides a classification criterion depends on whether classical and pseudobulges are cleanly separated in correlations between n and other parameters. In this sense, a tentative result shown in Figure 4 is encouraging. Several classical bulges for which high-accuracy n values are available satisfy the $n - M_V$ correlation observed for elliptical galaxies (e. g., Caon et al. 1993; Graham & Colless 1997; Fisher et al. 2005). In our photometry, all of these have $n > 2$. In contrast, all "bulges" that we have studied and that appear to be pseudobulges based on other criteria have $n < 2$. Work is in progress to enlarge the sample with very accurate n values and to further explore the above distinction (D. Fisher's PhD thesis).

5. It is more rotation-dominated than are classical bulges in the $V_{\max}/\sigma - \epsilon$ diagram; e. g., $V_{\max}/\sigma$ is larger than the value on the oblate line.

6. It is a low-σ outlier in the Faber-Jackson (1976) correlation between (pseudo)bulge luminosity and velocity dispersion.

7. It is dominated by Population I material (young stars, gas, and dust), but there is no sign of a merger in progress.

Small bulge-to-total luminosity ratios B/T do not guarantee that a galaxy contains a pseudobulge, but if $B/T \gtrsim 1/2$, it seems safe to conclude that the galaxy contains a classical bulge.

Based on these criteria, galaxies with classical bulges include M 31, NGC 3115, and NGC 4594. NGC 1353 (Figure 3) and many galaxies illustrated in KK04 contain prototypical pseudobulges. The classification of the bulge of our Galaxy is ambiguous; the box-shaped structure favors a pseudobulge, but stellar population data are most easily understood if the bulge is classical.

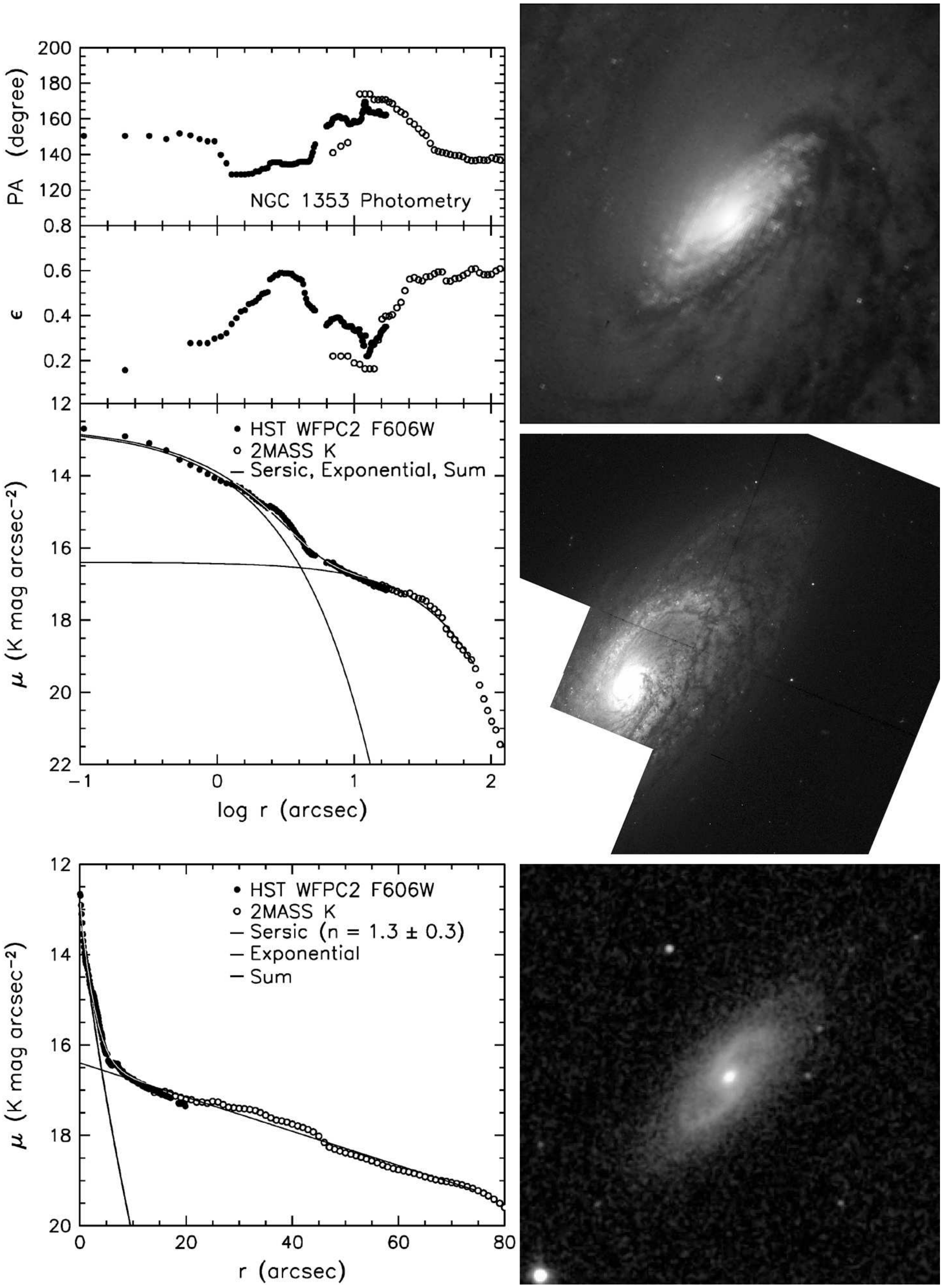

Fig. 3. NGC 1353 pseudobulge (top image: $18'' \times 18''$ zoom, and middle: full WFPC2 F606W image taken with *HST* by Carollo et al. 1998). The bottom panel is a 2MASS (Jarrett et al. 2003) *JHK* composite image with a field of view of $4\overset{\prime}{.}4 \times 4\overset{\prime}{.}4$. The plots show surface photometry with the *HST* profile shifted to the *K*-band zeropoint. The lines show a decomposition of the major-axis profile into a Sérsic (1968) function and an exponential disk. The outer part of the pseudobulge has the same apparent flattening as the disk. This nuclear disk produces much of the rapid upturn in surface brightness toward the center. From Kormendy & Kennicutt (2004).

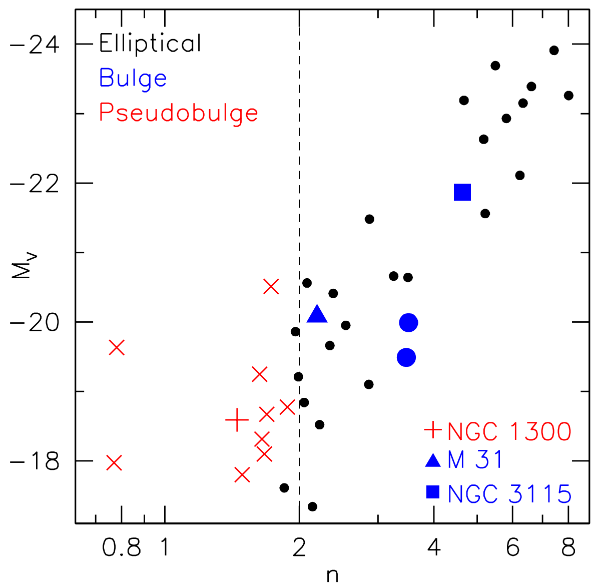

Fig. 4. Correlation of n with bulge absolute magnitude M_V for Virgo cluster elliptical galaxies (small filled circles, from Fisher et al. 2005), classical bulges (large filled symbols) and pseudobulges (crosses and plus signs). Three well known galaxies are identified.

5. GIVEN HIERARCHICAL CLUSTERING, HOW CAN THERE BE SO MANY BULGELESS, PURE-DISK GALAXIES?

Hierarchical clustering in a Universe dominated by cold dark matter (White & Rees 1978) accounts remarkably well for large-scale structure but has trouble explaining the internal structure of galaxies. One well known problem is affected by secular pseudobulge formation.

Hierarchical clustering produces merger violence. *How could so many bulgeless, pure-disk galaxies form without undergoing major mergers* (Tóth & Ostriker 1992; Freeman 2000)? Abadi et al. (2003b) note that if satellites are accreted with suitable geometry, they can add to the disk, not the bulge. This may help to explain old, thick disks (Mould 2005). But it helps only after the galaxy has become big enough so that inhaling a satellite is a minor accretion that results in satellite stripping, not violent relaxation that disrupts disks. By the time a galaxy gets this big, hierarchical clustering generally gives it a bulge (Steinmetz & Navarro 2002; Abadi et al. 2003a, b; Meza et al. 2003). Baryonic physics helps (reionization, supernova-driven energy feedback: Navarro, Eke, & Frenk 1996; Moore et al. 1999; Klypin et al. 1999). But this problem is hard.

We want to know how hard it is. Schechter & Dressler (1987) and Benson et al. (2002) estimate that approximately equal amounts of mass are incorporated into bulges and disks. This is based on photometric decompositions into $r^{1/4}$-law "bulges" and exponential disks.

But if secular evolution turns some disk material into pseudobulges that get confused with classical bulges in the above decompositions, then we overestimate the mass in classical bulges by a modest amount (KK04). The bulge-disk decompositions of Simien & de Vaucouleurs (1986) already suggest that late-type galaxies have very small bulges. Sbc, Sc, Scd, and Sd galaxies are found to have median bulge-to-total luminosity ratios of 0.17, 0.1, 0.03, and 0.02, respectively. When people try to understand this result in the context of hierarchical clustering, they hope that the gentlest part of the distribution of formation histories produces only a small merger contribution compared to dominant quiescent accretion. Still: "Reconciling . . . the properties of disk galaxies with the . . . high merging rates characteristic of hierarchical formation scenarios such as ΛCDM remains a challenging, yet so far elusive, proposition" (Abadi et al. 2003a).

The problem is worse for the numbers of classical bulges. We now know (KK04) that there is a sharp transition between Sb and Sc; Sb- and earlier-type galaxies mostly contain classical bulges; Sbc galaxies contain pseudobulges more often than bulges, and Sc- and later-type galaxies appear never to have classical bulges. This implies that a majority of field galaxies – not just a few, remarkably flat, edge-on, bulgeless disks (Matthews, Gallagher, & van Driel 1999; Freeman 2000; van der Kruit et al. 2001) – show no signs of major merger violence. The challenge for hierarchical clustering is correspondingly increased.

We emphasize: we are not trying to disprove hierarchical clustering. But we do see signs that pieces of the evolution puzzle are missing. Our aim is to put the observational challenge on as quantitative a footing as possible. We need a better determination of the luminosity functions of classical and pseudo bulges. This will lead to a better understanding of how far galaxies can evolve toward earlier Hubble types as a result of secular processes.

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