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KINEMATICS OF EXTRAGALACTIC BULGES: EVIDENCE THAT SOME BULGES ARE REALLY DISKS

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Abstract. Recent work on the dynamics of galaxy bulges has been dominated by two themes. (1) Bulges share the richness in kinematic structure that is currently being discovered in elliptical galaxies. This includes kinematic evidence for triaxiality and for accretion (counterrotating gas and stellar components). (2) The main subject of this paper is observational and theoretical evidence that some "bulges" are built secularly out of disk material. Many bulges show photometric and kinematic evidence for disklike dynamics. This includes (i) velocity dispersions σ much smaller than those predicted by the Faber-Jackson $\sigma - M_B$ correlation, (ii) rapid rotation $V(r)$ that implies V/σ values well above the "oblate line" describing rotationally flattened, isotropic spheroids in the V/σ – ellipticity diagram, and (iii) spiral structure dominating the $r^{1/4}$ part of the galaxy. In these galaxies, the steep, $r^{1/4}$-law central brightness profiles belong not to bulges but to disks. That is, some galaxy disks have central brightness profiles that are much steeper than the inward extrapolation of an exponential fit to the outer parts. These observations and n-body simulations of gas flow in nonaxisymmetric galaxies imply that high-central-concentration, flat components can be formed out of disk gas that is transported toward the center by bars and oval distortions. The n-body models suggest further that some "bulges" are built of disk stars heated in the axial direction by resonant scattering off of bars. These effects are signs that important secular evolution processes are at work in galaxy disks.

Key words: Galaxy Bulges – Galaxy Disks – Stellar Dynamics – Secular Evolution

1. Introduction

Observational and theoretical work on bulge dynamics is thriving; increasingly powerful tools provide us with much more information than we had a decade ago. Inevitably, bulge dynamics look more and more complicated. But two simple themes unify this work. One is well known: we see kinematic signatures of triaxiality and of galaxy accretion. This story is familiar from work on elliptical galaxies; I will review it only briefly (§ 2). The second theme is not well known; it will be the focus of this paper. A substantial body of evidence shows that some "bulges" are really disks: they have the steep, $r^{1/4}$-law brightness profiles that we associate with bulges, but they also have the "cold" (rotation-dominated) dynamics of disks. Numerical simulations suggest that they were built by various processes of secular evolution in disks, including inward gas transport by nonaxisymmetries in the potential and vertical heating by resonant scattering of stellar orbits off of bars. The importance of secular evolution driven by interactions with collective phenomena was emphasized by Kormendy (1982a, and references therein); §§ 3 – 7 bring these reviews up to date. Just as mergers showed that galaxies evolve not in isolation but in part through interactions, so the evidence for secular dynamical processes implies that internal evolution is more than the aging of stellar populations: the interactions of components can significantly change galaxy structure over a Hubble time.

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2. Stellar Dynamics of Bulges: Comparison With Elliptical Galaxies

2.1. The Dynamical Importance of Rotation

The "zeropoint" of this subject is well known (for reviews see Illingworth 1981; Kormendy 1982a; Binney 1982; Davies 1989; Kormendy and Djorgovski 1989, and de Zeeuw and Franx 1991). Work on elliptical galaxies was revolutionized by the discovery (Bertola and Capaccioli 1975; Illingworth 1977) that most bright ellipticals do not rotate significantly. Therefore their dynamics are controlled by velocity anisotropy, which implies that they are triaxial (Binney 1976, 1978a, b). Many observational signatures of triaxiality have been found. In contrast, bulges rotate essentially as rapidly as models of oblate spheroids that are isotropic and hence flattened only by rotation (e.g., Illingworth and Schechter 1982; Kormendy and Illingworth 1982; Kormendy 1982b); isotropic models are an excellent fit to the data (Jarvis and Freeman 1985a, b; Kent 1989). However, Davies *et al.* (1983) point out that most bulges are less luminous than the nonrotating ellipticals; low-luminosity ellipticals also rotate. It is therefore not clear whether bulges and ellipticals differ. The Sombrero Galaxy contains one of the few well-studied bulges that is as luminous as a typical nonrotating elliptical; it is an isotropic rotator, but so are a few bright ellipticals. Even now, too few high-luminosity bulges have been measured. We do not know whether virtually all bulges rotate rapidly or whether bulges and ellipticals show the same dependence of rotation on luminosity.

One complication (Kormendy and Djorgovski 1989) is that ellipticals can grow disks by accretion. If they originally did not rotate, they still will not rotate after becoming "bulges". They add noise to any intrinsic correlation between bulge rotation and luminosity.

Therefore we know of only modest dynamical differences between bulges and elliptical galaxies. Bulges lie nearly in the fundamental plane correlations for ellipticals (e.g., Kormendy 1985; Bender, Burstein, and Faber 1992). But there are some photometric differences (Hamabe and Kormendy 1987). Therefore a more quantitative comparison of bulges and elliptical galaxies may be profitable.

2.2. Kinematic (Sub)structure in Bulges and Elliptical Galaxies

Recent work on ellipticals has been dominated by continued attempts to measure the degree of velocity anisotropy and by discoveries of signatures of accretion. The latter include kinematically decoupled (misaligned) gaseous and stellar components. Reviews are given in Kormendy and Djorgovski (1989) and in de Zeeuw and Franx (1991). *This emerging richness in kinematic structure is shared by galaxy bulges.*

Kinematic evidence for accretion in disk galaxies includes the following. Gas that counterrotates with respect to the stars has been detected in NGC 4546 (Galletta 1987) and in NGC 2768, NGC 4379, and IC 4889 (Bertola, Buson, and Zeilinger 1992). We also have one spectacular case of an edge-on galaxy containing two stellar disks that counterrotate (NGC 4550: Rubin, Graham, and Kenney 1992; Rix *et al.* 1992). Bulges are less thoroughly studied than ellipticals; the early discovery of kinematically decoupled components in so many objects argues that bulge formation histories are as rich and complicated as those of elliptical galaxies.

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Ellipticals are triaxial; are bulges triaxial, too? It is fashionable to suspect that they are. But *this is not an argument by analogy.* In ellipticals, triaxiality follows from the *unimportance* of rotation, which implies that velocity dispersion anisotropy is needed to account for the flattening. Once we realized that σ_z is smaller than the other two components, we had no reason to expect that $\sigma_r = \sigma_\phi$, either. But bulges rotate rapidly enough to be isotropic. If they are triaxial, this is not because they are like nonrotating ellipticals but rather because they are like bars.

What do observations tell us? It is too early to tell. In one galaxy, NGC 4845, kinematic evidence for noncircular streaming motions has been found and interpreted as a sign of triaxiality (Bertola, Rubin, and Zeilinger 1989; Gerhard, Vietri, and Kent 1989). From slit spectra at five position angles, Bertola *et al.* (1989) conclude that the rotation velocity at $7'' - 10''$ radius is smaller along the major axis than elsewhere in the bulge. A slight twist between bulge and disk isophotes is also seen. In the absence of complications, these observations imply that the bulge is triaxial with principal axes $a : b : c \simeq 1 : 0.75 : 0.5$. The above papers agree reasonably well on the implied ranges of b/a and c/a. However, there are significant uncertainties. NGC 4845 is almost edge-on (inclination $i \geq 75°$). This means that the major axis (PA = 78°) and neighboring (PA = 44° and 98°) slits are separated by only $2''.8$ at $8''$ radius. How sure can we be that the velocities really differ when the deprojection corrections are factors of 2.9 and 1.8 for the two neighboring slits? Also, the galaxy is dusty; the brightness distribution clearly shows dust at radii of $\sim 5''$. Do we really see to the same depth along the line of sight at all three slit positions? Clearly this is a difficult object. Further such work is needed.

Bertola *et al.* (1989) note that NGC 4845 has a peanut-shaped bulge. Such bulges rotate particularly rapidly (§ 3); they may be related to or even formed by bars (§ 6). Peanut-shaped bulges are particularly likely to be triaxial.

3. Cylindrical Rotation in Box-Shaped Bulges

Kormendy and Illingworth (1982) found that in the box-shaped bulge of NGC 4565, rotation velocities remained almost constant with increasing height z above the disk plane to $z \simeq 30'' \simeq 2.7h^{-1}$ kpc (Hubble constant $H_0 = 50h$ km s^{-1} Mpc^{-1}). In contrast, rotation velocity decreased rapidly with increasing z in three galaxies with elliptical or disky-distorted bulge isophotes.

Cylindrical rotation is seen in all box-shaped bulges that have been observed. This includes the prototype, NGC 128 (Jarvis 1990; Bertola and Capaccioli 1977), which contains one of the most peanut-shaped bulges known (Sandage 1961; Jarvis 1990). In it, $V(z)$ is constant up to $z = 20'' = 8.5h^{-1}$ kpc. Three other box-shaped bulges have been measured and show cylindrical rotation, NGC 3079 (Shaw, Wilkinson, and Carter 1992), and NGC 1381 and NGC 7332 (Davies, Illingworth, and Kormendy 1993). Thus boxy bulges are particularly rapid rotators.

They also are more than just a curiosity. In a survey of all large, normal edge-on spiral and lenticular galaxies in the *Second Reference Catalog* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), Shaw (1987) found boxy bulges in $20 \pm 4\%$ of the objects. Therefore it is important to understand their origin.

Two mechanisms have been suggested. Most relevant to this paper is the

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suggestion that bars manufacture boxy bulges by vertical heating of the disk through resonant scattering of stellar orbits by the bar (see §6). An alternative mechanism based on accretion has been suggested by Binney and Petrou (1985), Jarvis (1987), Whitmore and Bell (1988), Hernquist and Quinn (1988), and Statler (1988). If a bulge or elliptical galaxy accretes a dynamically cold object at an oblique angle, then differential precession will phase-mix the orbits until they produce a boxy or X-shaped structure embedded in the bulge. This must happen. But in general we cannot tell whether a particular boxy bulge originated in this or some other way. An accretion origin has been proposed for the boxy distortions in IC 4767 (Whitmore and Bell 1988) and IC 3370 (Jarvis 1987). IC 3370 is an elliptical; it clearly shows cylindrical rotation.

Therefore it is likely that at least two different processes make boxy bulges. Since boxy ellipticals generally do not rotate significantly, they are made in still a third way. Only a few, mostly low-luminosity boxy ellipticals appear related to boxy bulges. Three mechanisms of origin are an inconvenience. However, it is easy to identify anisotropic ellipticals by their slow rotation, and boxy bulges can be built by a bar only if there is a substantial disk. Therefore the critical question is: how common are boxy distortions made by accretion?

4. Some Bulges Are Really Disks

It is not generally realized that many galaxies contain central components that look like bulges but that have disk-like dynamics. This section reviews the evidence. A remarkably large number of papers at this meeting address this subject; it is clearly an idea whose time has come. As in previous papers (Kormendy 1982a, b; Kormendy and Illingworth 1983), I suggest that high-density disks are formed from ordinary disk gas that has been concentrated toward the center and turned into stars.

4.1. NGC 4736

The prototypical bulgelike disk is in the Sb galaxy NGC 4736 (Kormendy 1982a). It is illustrated in the *Hubble Atlas* (Sandage 1961). The central brightness profile (Fig. 1) is an $r^{1/4}$ law that reaches the high central brightness characteristic of a bulge (Boroson 1981). However, the $r^{1/4}$-law component shows a nuclear bar and spiral structure to within a few arcsec of the center (Fig. 2). Bars are disk phenomena. More importantly, it is not possible to make spiral structure in a bulge. Thus the morphology already shows that the $r^{1/4}$-law profile belongs to the disk. This is shown more quantitatively by the well-known $V_{\rm max}/\sigma - \epsilon$ diagram (Illingworth 1977; $V_{\rm max}$ = maximum rotation velocity; σ = mean velocity dispersion near the center; ϵ = ellipticity). Figure 3 shows that the "bulge" of NGC 4736 has an unusually large ratio of ordered to random velocities (the data are from Pellet and Simien 1982). It is well above the "oblate line" describing oblate spheroids with isotropic velocity distributions. Disks observed edge-on are near the oblate line; $\epsilon \gtrsim 0.8$ and $V/\sigma \gtrsim 2$. Seen more nearly face-on, they project to positions above the oblate line. Kormendy (1982a) therefore concluded that most of the light near the center is coming from a high-surface-brightness disk.

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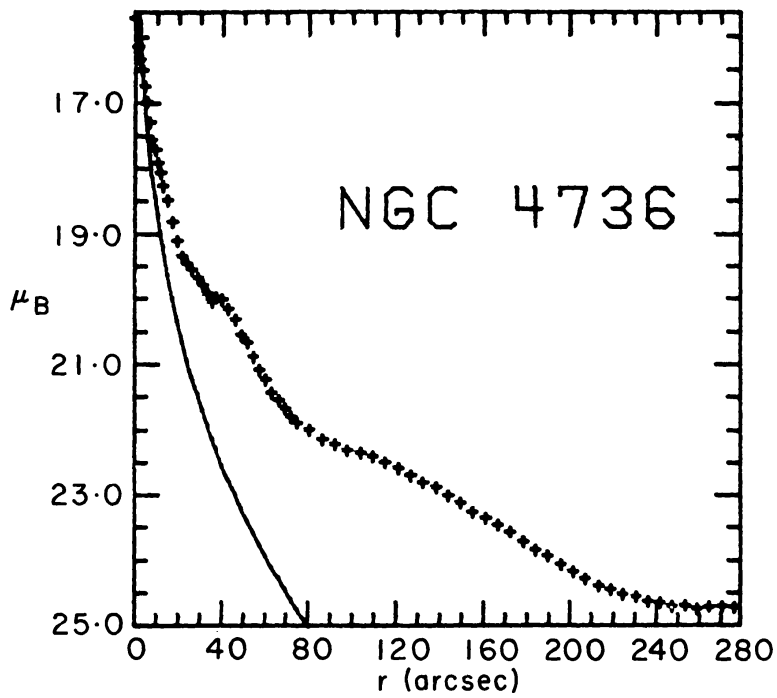

Fig. 1. Surface brightness profile of NGC 4736, from Boroson (1981). The "shelves" at 40″ and 120″ radius are characteristic of oval disks (Kormendy 1982a).

Fig. 2. CFHT image of NGC 4736 (106″ high). The radial brightness gradient has been removed: the image has been divided by a mask image with the brightness profile of the galaxy but exactly elliptical isophotes. The nuclear bar is elliptical and therefore also removed; it can be recognized by the spiral structure and dust morphology near the center.

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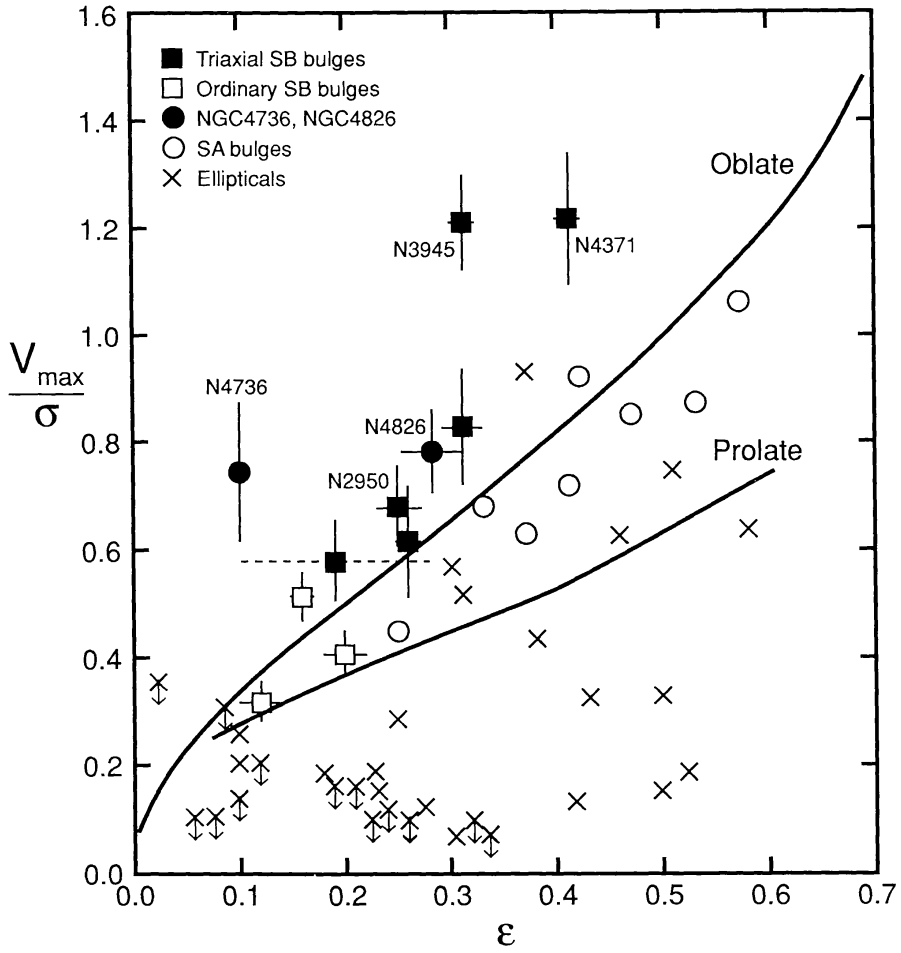

Fig. 3. $V_{max}/\sigma - \epsilon$ diagram for various kinds of stellar systems (cf. Kormendy 1982a).

4.2. NGC 4826

NGC 4826 (Fig. 4) is another prototypical example (Kormendy 1993). Sandage (1961) calls it the earliest-type Sb galaxy in the *Hubble Atlas*; normally such objects contain a bulge that resembles an elliptical galaxy. Although partially obscured by dust, the central brightness profile is approximately an $r^{1/4}$ law. Also, the central brightness is normal for a bulge and much higher than in typical disks. But NGC 4826 does not have the velocity dispersion of a bulge, as would have been implied by the published $\sigma = 160 \pm 16$ km s^{-1} (see Whitmore, McElroy, and Tonry 1985). In fact, the central velocity dispersion is very low, $\sigma = 90 \pm 5$ km s^{-1} (Fig. 5).

Figure 6 shows the Faber-Jackson (1976) correlation between σ and luminosity. NGC 4826 is well below the scatter for normal bulges. Whitmore, Kirshner, and Schechter (1979) and Whitmore and Kirshner (1981) long ago showed that some bulges have smaller dispersions than ellipticals of the same M_B. Kormendy and Illingworth (1983) found that most of these are in barred galaxies. There were two prominent examples among unbarred galaxies, NGC 1172 (E/S0) and NGC 7457 (S0, see § 4.3). NGC 4826 is very like these.

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Fig. 4. A V-band image of NGC 4826 taken with the CFHT. The scale is $0\farcs21$ pixel^{-1}; this panel is $210''$ wide. The Gaussian seeing dispersion radius is $\sigma_* = 0\farcs40$. Brightness and contrast have been adjusted to illustrate the dust disk; the central part of the bulge is saturated in this print. Compare the excellent photograph in the *Hubble Atlas*.

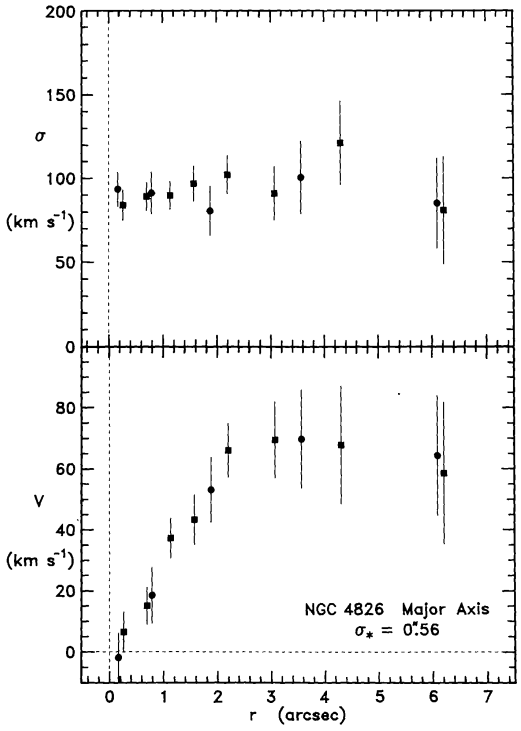

Fig. 5. Absorption-line rotation velocities V and velocity dispersions σ along the major axis of NGC 4826 (Kormendy 1993).

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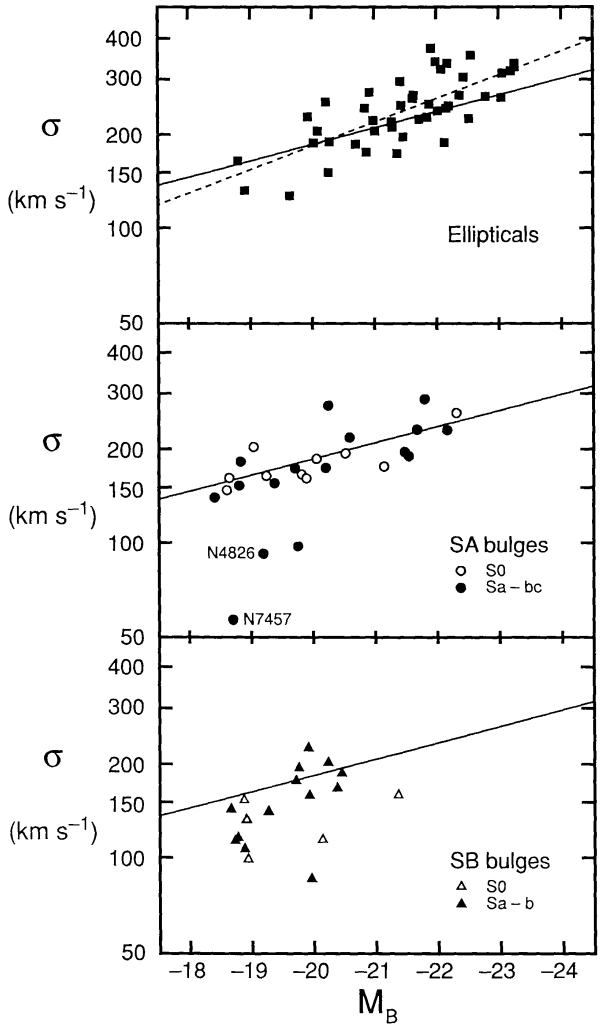

Fig. 6. Correlation between central velocity dispersion σ and absolute magnitude M_B for elliptical galaxies and for bulges of unbarred (SA) and barred (SB) disk galaxies. The solid line is a fit to the galaxies in the middle panel; the dashed line is a fit to the ellipticals. Except for the NGC 4826 point, this figure is from Kormendy and Illingworth (1983).

A small velocity dispersion is characteristic of disks. Kormendy and Illingworth (1983) and Kormendy (1982b) interpreted abnormally cold bulges as disk-like. A more definitive conclusion is provided by the $V/\sigma - \epsilon$ diagram (Fig. 3). Like NGC 4736, NGC 4826 is above the oblate line. Therefore much of the steep central brightness profile is coming from a cold component. A bulge may also contribute, but it does not dominate the light. Kormendy (1993) therefore concludes that the central disk light in NGC 4826 has the $r^{1/4}$-law brightness profile of a bulge.

Kormendy (1982b) found that many "bulges" of barred galaxies also are well above the oblate line in the $V/\sigma - \epsilon$ diagram. In particular, NGC 3945 and NGC 4371 are as dominated by rotation as NGC 4736. In all of these objects, the small σ (Fig. 6, bottom) and large V/σ (Fig. 3) show that the central components that we thought were bulges are really largely disk light.

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4.3. NGC 7457

As a final example of a "bulge" that is really a disk, consider NGC 7457. This is a normal, unbarred S0 (*Hubble Atlas*) dominated by an exponential disk (Kormendy 1977). The "bulge" is faint, fractionally and in absolute luminosity ($M_B \simeq -18.5$). *Hubble Space Telescope* observations by Lauer *et al.* (1991) show that it has a steep brightness profile, a very high central surface brightness ($\mu_{0V} \lesssim 12.4$ V mag arcsec^{-2}), and an unresolved core. The limits on the core parameters are extreme, but they are in the range expected for such a low luminosity (Fig. 7). This "bulge" is enormously different from a normal disk; these typically have $\mu_{0V} \simeq 21$ V mag arcsec^{-2} (Freeman 1970). The rotation curve has not been measured well enough to allow us to plot the galaxy in the $V/\sigma - \epsilon$ diagram. But $\sigma = 65$ km s^{-1}, making this the coldest "bulge" in Fig. 6.

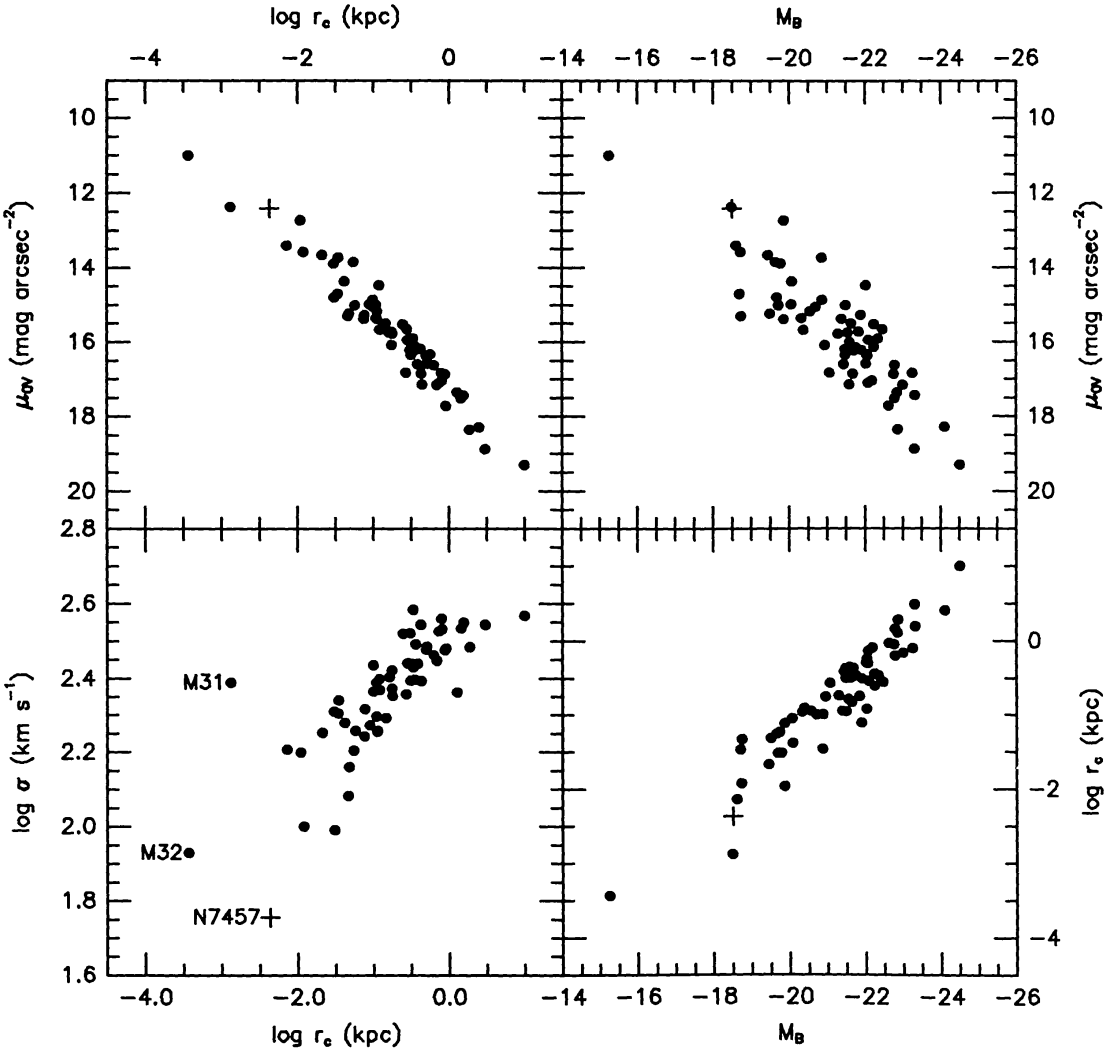

Fig. 7. Four of six fundamental plane correlations between core radius r_c, central surface brightness μ_{0V}, central velocity dispersion σ, and M_B. Approximate seeing corrections are from Kormendy (1987). NGC 7457 (Lauer *et al.* 1991) is shown by plus signs.

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4.4. Many "Bulges" Look As Flat As Disks

If some "bulges" are really disks, then this should be evident in the distribution of bulge ellipticities. Figure 8 shows this effect in bulge-disk decompositions computed by Kent (1985, 1987, 1988). I use only the decompositions in which the ellipticity of the bulge was a free parameter. Also, I include only objects with disk ellipticities $\epsilon_{\rm disk} \geq 0.14$, since face-on objects have no leverage on the problem. Bulge-disk decompositions are uncertain, so interpretation should be cautious. However, in agreement with Kent, I conclude that many bulges look as flattened as their associated disks. Some look more flattened; these may be triaxial.

The median ratio $\epsilon_{\rm bulge}/\epsilon_{\rm disk}$ is smallest for Sa galaxies and increases toward later Hubble types. This agrees with other evidence which suggests that disklike "bulges" are more common at later Hubble types. Finally, it is interesting that the median $\epsilon_{\rm bulge}/\epsilon_{\rm disk}$ for S0 galaxies is similar to that for Scs, not Sas. Kinematically disklike bulges also are more common in S0s than in Sas. Similar effects led van den Bergh (1976b) to develop his "parallel sequence" classification.

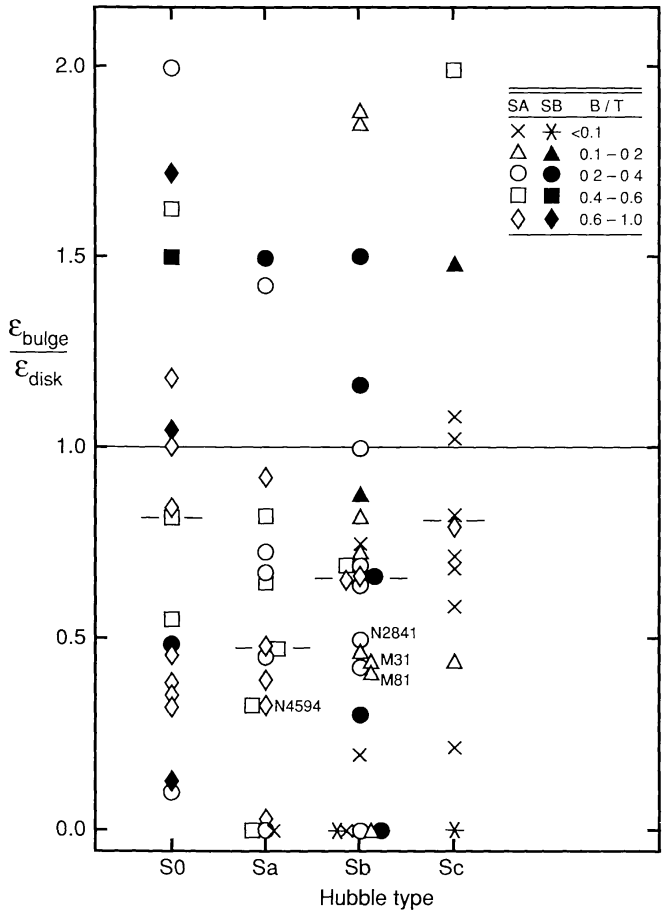

Fig. 8. Ratio $\epsilon_{\rm bulge}/\epsilon_{\rm disk}$ of bulge ellipticity to disk ellipticity, from bulge-disk photometric decompositions by Kent (1985, 1987, 1988). Different symbols encode bulge-to-total luminosity ratio B/T and the distinction between barred and unbarred galaxies (see key). Horizontal tics are drawn at the median $\epsilon_{\rm bulge}/\epsilon_{\rm disk}$ for each Hubble type.

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4.5. Nuclear Disks

"Nuclei" are central star clusters that are dynamically distinct from the bulge (see Kormendy and Djorgovski 1989 for a review). *Some nuclei are disks.* A particularly clear example is NGC 4594 (the Sombrero Galaxy): the nuclear isophotes are very flattened (Burkhead 1986, 1991; Kormendy 1988b), and even the observed spectrum, which is a composite of the bulge and nucleus, implies a velocity dispersion 181 ± 6 km s^{-1} at $r \simeq 3''.7$ that is smaller than the velocity dispersion 240 ± 4 km s^{-1} of the bulge (Kormendy 1988b; Jarvis and Dubath 1988). Another possible example is the nucleus of M 31: after subtraction of the superposed bulge spectrum, this is colder at $r \gtrsim 2''$ than the bulge (Kormendy 1988a, but contrast Dressler and Richstone 1988). Good spatial resolution is required to see a kinematic signature. More commonly, we recognize nuclear disks only through their effects on isophote shapes. Disky distortions in the central few arcsec of many ellipticals suggest that nuclear disks are common (Nieto *et al.* 1991; Scorza 1993). They are another example of high-density disk material near galaxy centers.

4.6. Triaxial Disklike "Bulges" In Barred Galaxies

In the discussion of the $V_{\rm max}/\sigma - \epsilon$ diagram, I noted that bulges of barred galaxies tend to be more dominated by rotation than bulges of unbarred galaxies. That is, they are more disk-like. Also, it has been known for a long time that many of them are triaxial. Examples include the SB0 galaxies NGC 1291 and NGC 1543 (de Vaucouleurs 1975; Jarvis *et al.* 1988) and NGC 2950 (Kormendy 1981). In all of these, the isophotes clearly show nuclear bars that have position angles different from the main bar and from the outer disk. Other examples are discussed in Kormendy (1979b) and in Buta (1986a, b, 1990). Sometimes the inner bar is a nucleus distinct from the bulge, sometimes the whole "bulge" in an SB galaxy is triaxial. Large $V_{\rm max}/\sigma$ values imply that these exceptionally triaxial "bulges" are dynamically like bars (Kormendy 1983; Kent and Glaudell 1989; Kent 1990) and not like triaxial giant ellipticals.

4.7. "Bulges" Made Of Population I Material

A suggestive clue to the origin of bulgelike disks is provided by their stellar content. Many of them contain or even are dominated by Population I material. For example, SB galaxies frequently contain nuclear hot spots of young stars and gas. Well known examples include NGC 1097 (Hummel, van der Hulst, and Keel 1987), NGC 4314 (*Hubble Atlas*), and NGC 4321 (Arsenault *et al.* 1988); general references are Sérsic and Pastoriza (1965), Alloin and Kunth (1979), and Buta and Crocker (1991). The same is true of "bulges" in some oval galaxies, including the prototype NGC 4736. Bulges are most likely to contain substantial Population I material at low luminosities and late Hubble types (Bica and Alloin 1987; Frogel 1992).

Even S0 bulges can contain molecular gas and star formation (e.g., at this meeting: NGC 4710, Wrobel and Kenney 1992, 1993; see many papers in Combes and Casoli 1991, but especially Sofue 1991). Also, a modest fraction contain older starbursts that give them A-type integrated spectra (e.g., Gallagher, Faber, and

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Balick 1975; Burstein 1979; Sparke, Kormendy, and Spinrad 1980; Sil'chenko 1993), although some of the young stars may result from accretion events. And central dust disks are very common in early-type galaxies, both S0s ("$S0_3$" objects in the *Hubble Atlas*) and ellipticals (see Kormendy and Djorgovski 1989 for a review).

Young stars are not always present: in early-type galaxies, $r^{1/4}$-law disks are usually made of old stars. However, the above observations show that when gas is present, it knows how to find the center and it likes to make stars there.

4.8. Conclusions

This section leads to two observational conclusions. First (Fig. 9): Besides true exponential disks and Freeman (1970) Type II exponentials, *some disks have steeper density profiles near the center than the inward extrapolation of an exponential fitted at large r. Disks can even have $r^{1/4}$-law central brightness profiles, in which case they are indistinguishable from bulges on the basis of density or density gradient alone.* They can often be recognized by V_{max}/σ values that are larger than normal for isotropic spheroids of the observed ϵ (however, see § 6). I do not mean to imply that there is no bulge at all in all of these galaxies; at least at early Hubble types, the high-density disk material has probably been added to a preexisting bulge. But in extreme cases, the disk dominates the projected density.

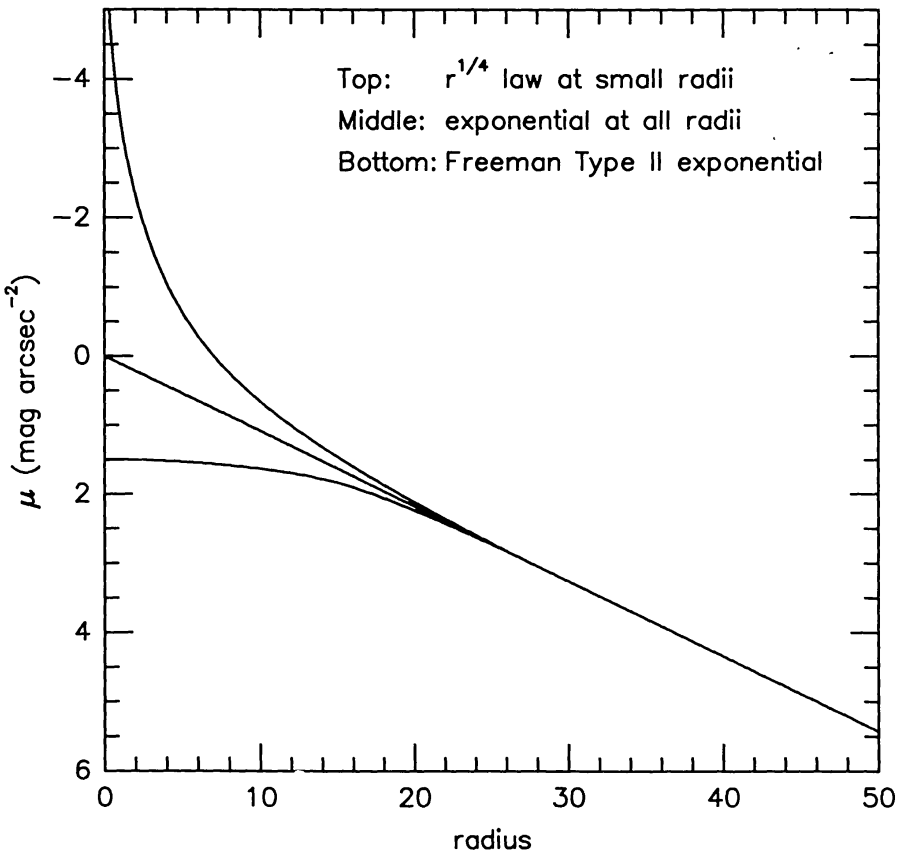

Fig. 9. Schematic disk brightness profiles.

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Second (Fig. 10): If we want B/T to measure the true bulge-to-total luminosity ratio, i.e., the fraction of the total light that is contributed by an ellipsoidal component that is more-or-less like an elliptical galaxy, then *the true distribution of bulge-to-total luminosity ratios is skewed toward smaller values than those we derive from a blind decomposition of luminosity distributions into $r^{1/4}$-law and exponential parts.* At all Hubble types, this effect is most common in barred and oval galaxies. Otherwise, it is smallest at early Hubble types, where most bulges are like ellipticals (except in some S0s). At type Sb, there are already some galaxies in which most of the "bulge" is really disk material, although others (e.g., M 31 and M 81) contain true bulges. By type Sc, I do not believe that any galaxies contain true bulges.

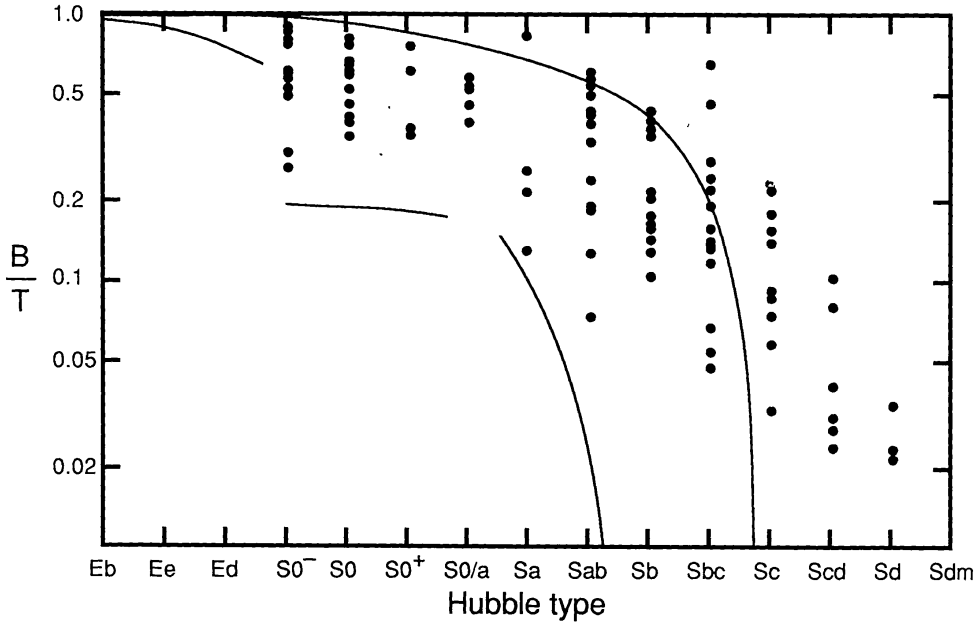

Fig. 10. Schematic distributions of true bulge-to-total luminosity ratios. This figure is adapted from Fig. 2 in Simien and de Vaucouleurs (1986); Eb, Ee, and Ed refer to ellipticals with boxy, elliptical, and disky isophotes, respectively. The points are values measured by decomposing profiles into $r^{1/4}$-law and exponential parts. The curves estimate how the boundaries of the B/T distributions change if we include disk-like "bulges" with disks. More accurate B/T distributions should ultimately be based on dynamical data.

5. Building "Bulges" By Secular Evolution. I. Making Bulgelike Disks By Bar-Driven Inward Gas Transport

A unifying hypothesis for the origin of bulgelike disks emerges from discussions by a number of authors (e.g., van den Bergh 1976a; Kormendy 1982a,b, 1988b; Gallagher, Goad, and Mould 1982; O'Connell 1983; Kormendy and Illingworth 1983; Kormendy and Djorgovski 1989; Kormendy and McClure 1993). The suggestion is that *the central concentration of galaxy disks can be increased dramatically by inward gas transport and subsequent star formation. Bars and oval disks are particularly efficient engines for this process* (see Kormendy 1982a; Prendergast 1983; Combes 1991 for reviews).

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This idea also is a natural consequence of the hypothesis that nuclear activity in galaxies results when black holes are fueled by infalling gas. If gas can reach the black hole, it may form stars along the way when the density gets high enough in the gravitational funnel. This may even be a necessary step in the formation of nuclear black holes, since core collapse times in giant ellipticals are long, while nuclei can evolve more rapidly (Kormendy 1988c).

Shlosman and Begelman (1987, 1989) and Shlosman, Frank, and Begelman (1989) take this idea one step further and suggest that hierarchical bar formation through inward gas transport also solves the problem of how to get fuel to small radii where the main bar no longer affects the gravitational potential. They suggest that a bar transports gas inward to radii much smaller than its length; at this point the central concentration has increased enough to make the gas self-gravitating; it becomes unstable to the formation of a new and shorter bar, and the process repeats itself with residual gas. It is not clear that all of this actually happens, nor is it clear that this is the dominant transport process (contrast Gunn 1979). But it is interesting to note that the nuclear bars discussed in the previous section are predicted by the Shlosman and Begelman mechanism. *Space Telescope* observations should tell us whether there exist additional levels of bar-within-bar hierarchy.

There has recently been a resurgence of theoretical work on the building of nuclear disks and bulges by secular processes. For example, Hasan and Norman (1990), Norman and Hasan (1990), and Hasan, Pfenniger, and Norman (1993) point out that bars may be destroyed when the central mass concentration is increased sufficiently. Related papers include Duschl (1988a, b) and Pfenniger and Norman (1990). Many papers at this meeting also discuss aspects of this picture (Gerhard 1993; Hasan and Norman 1993; Sellwood 1993; Wada and Habe 1993).

6. Building "Bulges" By Secular Evolution. II. Making Box-Shaped Bulges By Bar-Driven Vertical Disk Heating

The previous section suggests that bars increase the central mass concentration of disks, but it does not explain how to make bulges that are thick in the axial direction. This section reviews a heating process that may allow bars to manufacture box-shaped bulges out of disks. This has clearly captured the interest of the n-body modeling community; it has been discussed repeatedly at this meeting.

The idea is this: at radii where the vertical oscillation frequency ν_z of disk stars is in resonance with the pattern speed Ω_B of the bar, the vertical motions are amplified by the bar. The most important such resonance is vertical inner Lindblad resonance (ILR), $\Omega_B = \Omega - \nu_z/2$ (Ω is the angular velocity of rotation about the center). At vertical ILR, the z oscillations look periodic to the bar, so perturbations accumulate quickly. The effect is analogous to azimuthal disk heating at planar ILR by bars and spiral arms. The result is that the disk thickens. Many authors have developed this picture; they show that the result is a rapidly rotating box-shaped "bulge" (Combes and Sanders 1981; Pfenniger 1984, 1985; Combes *et al.* 1990; Pfenniger and Norman 1990; Friedli and Pfenniger 1990; Pfenniger and Friedli 1991; Raha *et al.* 1991). A number of papers at this meeting further develop the theme (Friedli and Udry 1993; Hasan and Norman 1993; Pfenniger 1993; Sellwood 1993).

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The process is attractive because it is specific (we can simulate it rigorously) and because it seems to work. The heating must happen. It also agrees in important ways with the observations: the resulting box-shaped bulges rotate cylindrically. But we do not yet know whether this process is sufficient in practice or whether it is the main process making boxy bulges. I am especially concerned about the extreme view that boxy bulges are bars seen side-on:

(i) Edge-on bars are very flat, and in some cases they coexist with a boxy bulge. One example is NGC 4762 (*Hubble Atlas*; Wakamatsu and Hamabe 1984).

(ii) If boxy bulges are side-on bars, then the longest major axes of boxy bulges should equal the lengths of bars in face-on galaxies.

(iii) The distributions of luminosity and B/T ratio for boxy bulges should equal the analogous distributions for bars in face-on galaxies.

Predictions (ii) and (iii) can be checked observationally. I suspect that all three points will be problems for the idea that boxy bulges are side-on bars. But I know of no observation that conflicts with the idea that boxy bulges are manufactured by vertical heating of the centrally concentrated disks discussed in §§ 4 and 5.

7. Conclusion: Our Galaxy

The main conclusion of this paper is that some "bulges" are disk-like in their dynamics and origin. That is, disks can have central brightness profiles that are much steeper than exponentials; in extreme cases, they are as well fitted by $r^{1/4}$ laws as are ellipticals. Then true bulge-to-total light ratios are smaller than we think. One consequence is that we should be cautious in interpreting evidence for bulge triaxiality; we may be seeing disk effects.

Although the details are far from clear, we believe that all this results from one or more processes of secular dynamical evolution. Bars and oval disks are particularly likely engines, but dissipation and gas infall can happen without them, and a variety of processes may operate. The importance of secular evolution by the interaction of galaxy components has been emphasized by Kormendy (1979a, b, 1981, 1982a).

The above results are particularly relevant to this meeting because our Galaxy has probably been affected. It is an Sbc (de Vaucouleurs and Pence 1978), so it is unlikely to contain a pristine, pure bulge (Fig. 10). It is barred. The beautiful COBE photograph of the Galaxy (Mather *et al.* 1990; see the Bahcall Committee report for a color version) shows that its bulge is box-shaped. Massive molecular clouds live near the center. We should be on the lookout for young stars. The age of the bulge has been the most controversial subject discussed at this meeting; surely the stars at large z are old, but does the bulge contain young stars near the disk plane? *If external galaxies are any guide, it is likely that our Galaxy has had its bulge augmented by high-density disk material and that active star formation continues near the center.* Were this not so, our Galaxy would be quite unusual. When we discuss the stellar population, the dynamics, and the evolution of the Galactic bulge, we should ask: *Are some effects that we see properties not of a true bulge but rather of a high central concentration of disk material that may have been heated by instabilities and resonance effects?* I believe that it will be important to look for the effects discussed in §§ 4 – 6 in our own front yard.

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DISCUSSION

Statler: You say there might not be bulges in some galaxies, they're really just the disks. What do you mean by a disk? When I think of a disk, I think of something that's very flat. When I look at the side of NGC 4826, at least to the eye and unless the gas distribution is very asymmetric, it looks like it has a thick bulge that is poking up above the back side of the dust lane.

Kormendy: In NGC 4826, you can't tell what the apparent axial ratio of the disk is, because the exposure is too short. It would require looking at ellipticity as a function of radius out where the disk is, which is not evident on the slide you are referring to. But, I was not trying to say that all the material is disk material or that this object has no bulge whatsoever. You also asked, what's a disk anyway? That is a question to which none of us has formulated a rigorous answer. But I can give you some qualitative idea of what the picture in my mind is. If you look at the V/σ–diagram for edge-on objects, which as you say are if they are not triaxial somewhere around the ridge-line, disks live up where the ratio is much larger than the most flattened ellipticals (E6). So if you see an object of E9, I would call that a disk. If you see an E3, call it a spheroid. But the dividing line is only as sharp as nature makes it and we should not be surprised if there is not a sharp boundary.

Statler: If you're looking at the V/σ–diagram, you have to be very careful of interpreting $V/\sigma > 1$ as being a disk signature (with respect to the oblate isotropic line). Isotropy is of course just a middle case and there is nothing preventing you from having a thickened ellipsoidal object that is slightly tangential, or radially cold and vertically hot. Of course there are formation problems associated with that. But if it is radially cold, and you want to make the bulges out of vertical heating by Pfenniger, Norman or Sellwood's mechanisms, bars are radially hot rather than radially cold. So I don't really see how you would get a disk-like low velocity dispersion object from this bar mechanism which makes things radially very hot.

Kormendy: On the second point: I wasn't trying to suggest that the vertical heating produced that bar, or that it was the only way to produce a thickened object. I was mainly bringing that up in connection with the box shaped objects, and the connection there does not seem too bad, although I do have some worries with it.

Tendrup: We (Davies *et.al.*) are completing a survey of 60 or 80 inner regions of spiral galaxies in *JHK*, where the effects of dust are minimized. We have a large number of galaxies for which, although the profile changes from exponential to identically $r^{1/4}$ within a certain radius, there is no change in anything like color or ellipticity. Just as though you have an elliptical galaxy stuck in a disk. You could decompose them, but they don't look like what we would normally think of as a bulge oldish population and a disk with somewhat younger population. On

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the other hand, there are galaxies that can be separated quite well into bulge and disk components. We don't have enough data to do statistics on this, but there are several examples. As a particular example, when you do K-band imaging, a lot of Sb galaxies have a lot more triaxial signatures in them, than you would see in the optical, since you can see right through at K.

Kormendy: So you see at K some bulges that are as flattened as disks. These are very welcome observations, because it is clear that this game should be played further into the IR where dust and young stars mess up the story much less.

Renzini: Is it possible to attempt a quantitative estimate of the amount of star formation of the bulges for two cases in particular, the Galactic bulge and that of M31?

Kormendy: In M31, there are only two observations (that I know about), that point to this kind of phenomenon. M31 is a classic example of a relatively ordinary elliptical-galaxy-like bulge, but it is true that there are clear signs that the dust distribution that belongs to the disk, extends inside the bulge. Not very much light needs to be invoked, but the nucleus is almost negligible in terms of its fractional light contribution. So M31 happens to be a galaxy which has this disease, clearly in the central 2 arcsec, but that almost doesn't count in terms of mass. In our own Galaxy, I would love to know the answer and I have been listening very carefully to see whether elements of this are coming out in this meeting. But one of the things that is very likely to happen, is that this phenomenon is a strong function of z-distance. Much of the work we have seen, such as on Baade's window, is already at moderately large z-distances. So we want observations much nearer to the centre. Perhaps the OH/IR stars are an indication, but then the ages of those stars have been debated here, so we just don't have all the answers yet.

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