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A PROPOSED REVISION OF THE HUBBLE SEQUENCE FOR ELLIPTICAL GALAXIES

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ABSTRACT

The Hubble classification scheme has a well known drawback for elliptical galaxies: the sequence E0–E6 correlates primarily with inclination and not with fundamental properties. In contrast, later-type galaxies are ordered by fundamental physical parameters. We propose to revise the Hubble sequence so that it orders ellipticals by isophote shape. Specifically, we suggest that the Im–spiral–S0 sequence be connected to disky ellipticals and thence to boxy ellipticals. The sequence is continuous from S0s to disky Es. However, boxy Es may be unrelated to other ellipticals: global and core properties both show signs of a dichotomy between (1) normal- and low-luminosity ellipticals that rotate rapidly, that are nearly isotropic and oblate-spheroidal, that are coreless, and that have *disky-distorted isophotes*, and (2) giant ellipticals that are essentially nonrotating, that are anisotropic and moderately triaxial, that have cuspy cores, and that are *boxy-distorted.* In the classification, we use isophote shape as an implicit indicator of velocity anisotropy. Two observations support this interpretation: (1) ellipticals with disky isophote distortions rotate rapidly while boxy ellipticals tend to rotate slowly; (2) disky ellipticals show little minor-axis rotation while boxy ellipticals often have large amounts of minor-axis rotation. An approximate classification by velocity anisotropy extends the Im–spiral–S0 sequence through the ellipticals in a physically reasonable way, and it is diagnostic of formation mechanisms. Care is required to recognize unfundamental complications such as the building by accretion of disky substructure inside a boxy elliptical. However, we believe that the proposed scheme distills the essential physics that should be embodied in a relevant morphological classification.

Subject headings: galaxies: elliptical – galaxies: internal motions – galaxies: photometry – galaxies: structure

1. INTRODUCTION

Galaxy morphology aims to classify objects into a small number of "natural groups" that isolate common structural features (Morgan 1951). Sandage & Bedke (1994) emphasize that no attempt is made to attach physical interpretation to classical morphology. This is the safe course when we know little about a subject. However, a classification remains useful as the subject matures only if the natural groups succeed in ordering objects in a physically interpretable way. E. g., Morgan's (1958) "form classification" identifies the important cD phenomenon (Morgan & Lesh 1964); this is not contained in other classifications, so it is widely used. Otherwise, form classes do not distill physics as well as alternative classifications, so they are rarely used. The most popular classification scheme is that of Hubble (1936), Sandage (1961, 1975), and Sandage & Bedke (1994), with refinements by de Vaucouleurs (1959). It is successful precisely because it orders galaxies by properties that reflect essential physics.

However, Hubble types have a well known shortcoming for elliptical galaxies (Tremaine 1987). The sequence E0–E6 is one of apparent flattening. But this must mainly be a sequence of inclinations, because ellipticals have only a modest range of true flattenings (Sandage, Freeman, & Stokes 1970; Binney & de Vaucouleurs 1981; Tremblay & Merritt 1995). Also, galaxies can be flattened for at least two reasons, rotation and velocity anisotropy (Illingworth 1977; Binney 1978). So the E0–E6 sequence is not as fundamental as that from S0 to Im. Meanwhile, a wealth of new discoveries has revolutionized our understanding of the structure and formation of ellipticals (see Binney & Tremaine 1987 for a review). Tremaine (1987) emphasizes that an ideal morphology should embody this understanding.

In response to the above challenge, we suggest a classification that is intended to order ellipticals by velocity anisotropy. This is the natural way to extend Hubble types: from Sc–Sb–Sa–S0–E, rotation decreases in dynamical importance compared to random motions; then, within the E sequence, rotation becomes unimportant and the dynamics become dominated by velocity anisotropy. The proposed revision contains the essential physics of modern work on ellipticals. However, the obvious problem is that anisotropy is not directly measurable. Section 2 suggests a practical alternative: we order galaxies by how their isophote shapes depart from ellipses. Sections 3 and 4 show that these distortions measure anisotropy. Section 5 discusses complications. This paper is part of the development of a "physical morphology" (Kormendy 1982) whose aim is to construct a classification scheme that is based on our physical understanding of galaxies.

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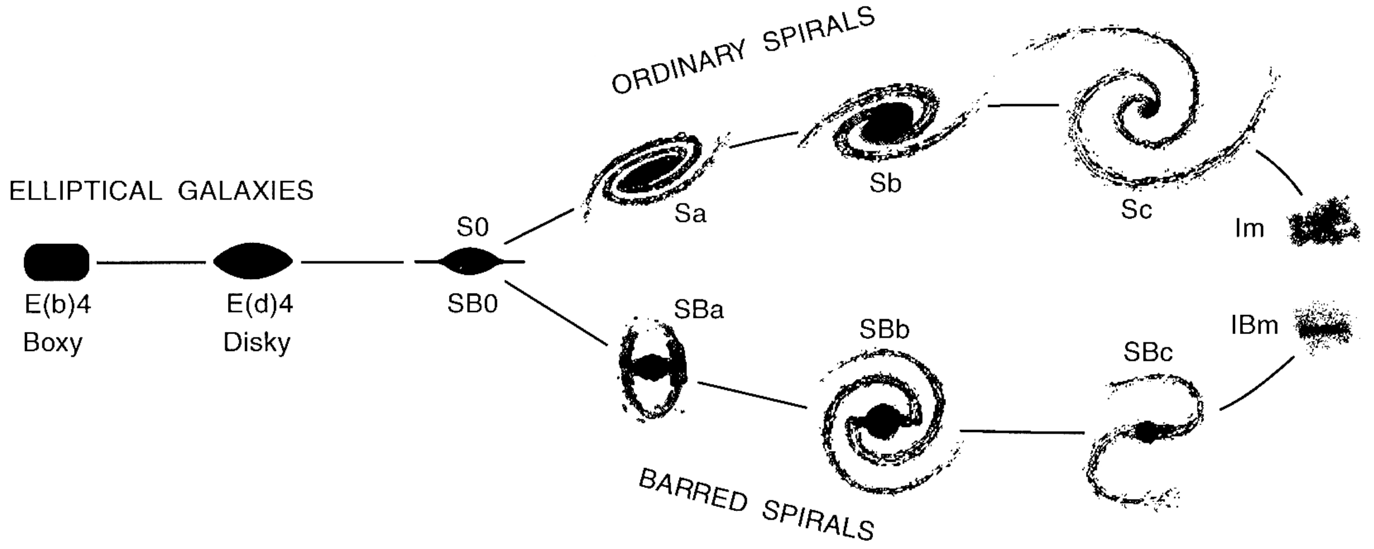

FIG. 1.—Proposed morphological classification scheme for elliptical galaxies. Ellipticals are illustrated edge-on and at ellipticity $\epsilon \simeq 0.4$. The connection between boxy and disky Es may not be continuous (§ 4). This figure is based on the tuning-fork diagram of Hubble (1936). We make three additional modifications: we illustrate the two-component nature of S0s and label them as barred or unbarred; we call unbarred spirals "ordinary" rather than "normal" (de Vaucouleurs 1959), and we add Magellanic irregulars.

2. CLASSIFICATION SCHEME FOR ELLIPTICAL GALAXIES

Fig. 1 illustrates the proposed classification. Smoothly connecting onto S0s are "disky" ellipticals, i. e., those with isophotes that are more elongated along the major axis than best-fitting ellipses. Next come "boxy" ellipticals, i. e., those with isophotes that are more rectangular than ellipses. We illustrate the classification with Hubble's (1936) tuning-fork diagram; clearly it can be incorporated into de Vaucouleurs' (1959) more detailed classification.

Ellipticals with exactly elliptical isophotes are omitted; we consider them as intermediate between disky and boxy ellipticals in the same way that Sab galaxies are intermediate between the primary types Sa and Sb. However, we also show in § 4 that they are mainly face-on versions of the above two types. Unfavorable inclination inevitably makes classification difficult. For spirals, edge-on inclination is unfavorable; for ellipticals, a face-on view can make classification by isophote shape impossible.

Like previous authors, we will parametrize isophote distortions by the amplitude a_4 of the $\cos(4\theta)$ term in a Fourier expansion of the isophote radius in polar coordinates (see, e. g., Bender 1987; Bender, Döbereiner & Möllenhoff 1988, who also illustrate prototypical examples). The use of a_4 as a classification parameter is faithful to the descriptive methods of classical morphology based on direct images. The only difference is that isophote distortions are subtle: only the most extreme galaxies can be classified by eye without isophotometry. Along the major axis, the fractional radial departures from ellipses are typically $|a_4/a| \simeq 1\,\%$. Positive values of a_4/a describe disky isophotes, negative values describe boxy isophotes.

The proposed classification requires a convenient notation. We retain apparent flattening as in the Hubble sequence. Conservatively, we add a descriptor of isophote shape and not a code for its interpretation. In the spirit of Hubble classification, we denote as E(d)4 an elliptical that has ellipticity $\epsilon = 0.4$ and a disky distortion. E(b)4 is a similar elliptical that is boxy. If more detail is required, then for example, E(b1.5)4 can denote an elliptical whose boxy distortion has a mean amplitude of 1.5 %.

3. EVIDENCE THAT ISOPHOTE SHAPES MEASURE ANISOTROPY

Our discussion of isophote shapes follows Bender *et al.* (1989: B+89) and Kormendy & Djorgovski (1989).

Evidence that a_4/a measures anisotropy is summarized in Figure 2. The upper panel plots $(V/\sigma)^*$, the ratio of the rotation parameter V/σ to the value for an isotropic oblate spheroid flattened by rotation (Davies *et al.* 1983; V is the maximum rotation velocity and σ is the mean velocity dispersion inside one-half of the effective radius). The correlation of $(V/\sigma)^*$ with a_4/a shows that rotation is dynamically less important in boxy than in disky ellipticals (Bender 1987, 1988; Nieto, Capaccioli, & Held 1988; Wagner, Bender, & Möllenhoff 1988; B+89; Nieto & Bender 1989; Busarello, Longo, & Feoli 1992; Bender, Saglia, & Gerhard 1994). All disky ellipticals show significant rotation, and many are consistent with isotropic models. Boxy ellipticals have a variety of $(V/\sigma)^*$ values but include all of the galaxies with negligible rotation. Values of $(V/\sigma)^* \ll 1$ are a direct sign of anisotropy.

The lower panel shows minor-axis rotation velocities normalized by an approximate total rotation velocity. Disky ellipticals are major-axis rotators. Boxy ellipticals include the minor-axis rotators. Fig. 2 (*bottom*) is new here, but signs of the above effect were seen in Davies & Birkinshaw (1986), Wagner *et al.* (1988), and Capaccioli & Longo (1994). Minor-axis rotation is also a direct sign of anisotropy (see de Zeeuw & Franx 1991 for a review).

We conclude that a_4/a is a convenient and reasonably reliable measure of velocity anisotropy. A better index could be constructed by combining a_4/a with indices based on the parameters in Figure 2. However, this would require kinematic data, so it would be available for relatively few objects. Figure 2 justifies our suggestion that isophote shape provides a practical classification index.

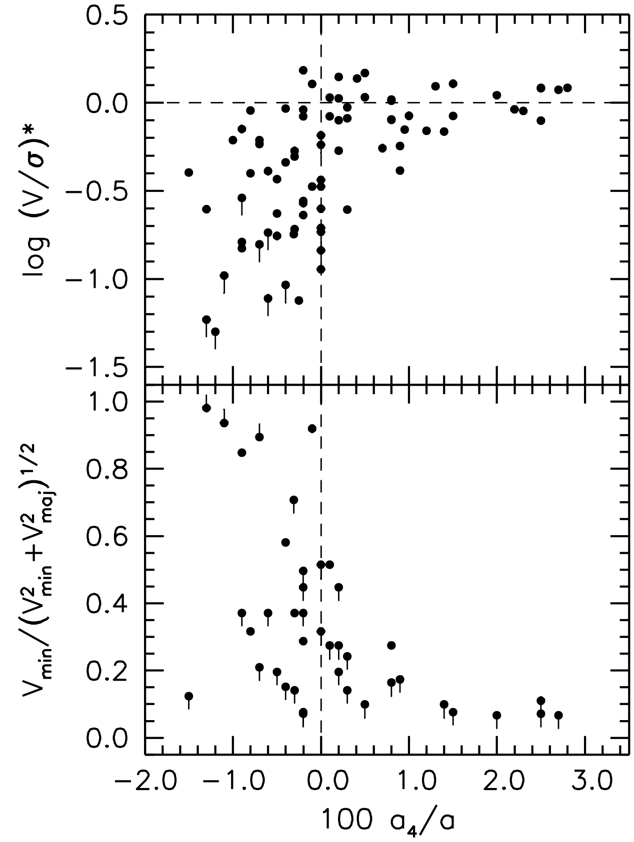

FIG. 2.—Correlations with isophote shape of parameters that are diagnostic of velocity anisotropy. Here $100\,a_4/a$ is the percent inward or outward perturbation of isophote radii along the major axis; negative values imply boxy isophotes; positive values imply disky isophotes. The upper panel shows the rotation parameter $(V/\sigma)^*$ (from Bender 1988, with a_4/a values from B+89 and with $(V/\sigma)^*$ values added from Davies *et al.* 1983). The lower panel shows maximum minor-axis rotation velocities normalized by total rotation velocity.

4. IS THE SEQUENCE OF ELLIPTICALS CONTINUOUS?

It is not clear that the E sequence in Fig. 1 is continuous. By continuous, we mean that there exist galaxies at all transition stages from S0s to extremely boxy ellipticals. A corollary would be that the formation process varies continuously from S0s through disky Es through boxy Es.

The discussion so far is consistent with continuity. In particular, the likelihood that disks are hidden in many Es and therefore that the S0–E(d) sequence is continuous has been emphasized many times (Kormendy 1979; Capaccioli 1987; Carter 1987; Bender 1988, 1990, 1992; Capaccioli & Longo 1990; van den Bergh 1990; Capaccioli *et al.* 1990; Rix & White 1990; Capaccioli & Caon 1992; Scorza 1993; Scorza & Bender 1995).

One reason to suspect a discontinuity is shown in Fig. 3. This shows the correlation of ellipticity with a_4/a. As noted by B+89, the distribution of points is V-shaped. Nearly elliptical Es are almost round. Flattened ellipticals tend to be boxy or disky. Intrinsically, the most common shape is $\sim$ E4; spherical objects are rare (references in § 1). Therefore the most boxy and disky galaxies are seen nearly edge-on, and elliptical ellipticals are seen nearly face-on. B+89 suggest that essentially all ellipticals are boxy or disky when seen edge-on. This implies a dichotomy.

Additional evidence for a dichotomy between two kinds of ellipticals was discovered by Nieto *et al.* (1991). In their

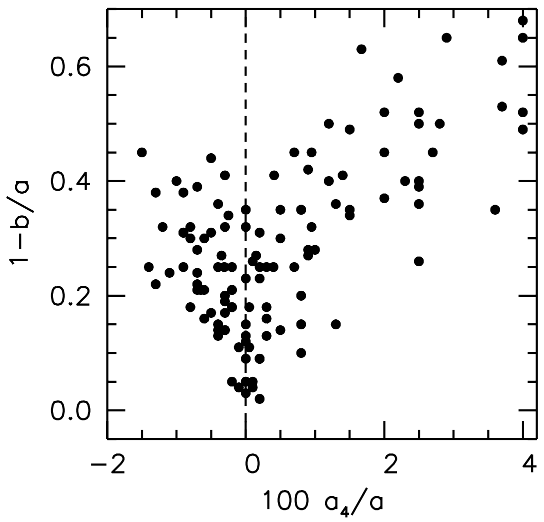

FIG. 3.—Ellipticity versus a_4/a (B+89, plus new data).

sample, no elliptical with disky isophotes showed a core. All resolved cores were in boxy galaxies. This conclusion is confirmed by *Hubble Space Telescope* photometry: most giant ellipticals have "cuspy cores", i. e., shallow power-law profiles interior to a break radius that separates the core from the steep outer profile (e. g., Lauer *et al.* 1992; Crane *et al.* 1993; Kormendy *et al.* 1994; Ferrarese *et al.* 1994; Lauer *et al.* 1995), but cuspy cores are seen only in boxy ellipticals. That is, the distribution of profile slopes in the inner $0\farcs1$–$0\farcs5$ is bimodal, with one peak at $d\log I/d\log r \simeq 0$ to -0.26 (these are cores) and another at -0.5 to -1.2 (implying coreless, power-law profiles) (Kormendy *et al.* 1994, 1996; Gebhardt *et al.* 1996; Faber *et al.* 1996). From these papers and from Fig. 2 and 3, above, we suggest that *there is dichotomy between (1) normal- and low-luminosity ellipticals that rotate rapidly, that are nearly isotropic and oblate-spheroidal, that are coreless, and that have disky-distorted isophotes, and (2) giant ellipticals that are essentially nonrotating, that are anisotropic and moderately triaxial, that have cuspy cores, and that are boxy-distorted.* The two types of ellipticals overlap in luminosity. The dichotomy is further justification for the two classes of ellipticals in Figure 1.

The dichotomy is suggestive but not certain. Fig. 2 and 3 are consistent with two alternatives (B+89; Kormendy & Djorgovski 1989). (1) It is possible that boxy and disky ellipticals form a continuous but not uniformly populated sequence that connects to S0s at one end. As rotation decreases, galaxies become more spherical and anisotropic. Farther along the sequence, the most anisotropic galaxies are again flattened and turn out to be boxy. (2) Perhaps only the disky ellipticals are the continuation of the Im–S0 sequence, and boxy ellipticals are a separate group with a different origin. Both alternatives are consistent with the proposed classification. Further work is needed to test the suggested dichotomy and its possible implications.

5. COMPLICATIONS

It is unrealistic to hope that the rich phenomenology of elliptical galaxies can be summarized as simply as in Figure 1. This section discusses complications.

First, it is clear that there are two kinds of boxy structure (Bender 1988; Nieto & Bender 1989). High-luminosity boxy ellipticals include the slowest rotators. But boxy bulges of disk galaxies rotate rapidly (Kormendy

& Illingworth 1982). A few low-luminosity box-shaped ellipticals rotate rapidly, too (Nieto & Bender 1989). All are companions of much more luminous galaxies, suggesting to the above authors that the boxy structure is related to interactions. We believe that these objects are fundamentally different from boxy ellipticals. They are boxy because they rotate "too much" (there is an excess of tube orbits), while E(b) galaxies are boxy because they rotate "too little" (they are anisotropic). We identify the rapidly rotating boxy ellipticals with boxy bulges. This type of boxyness is not included in the classification.

The second complication is that a_4/a can change sign with radius. In some galaxies, boxy and disky distortions coexist at the same radius. What does this mean?

It is no surprise that a_4/a can change sign with radius. The amount of dissipation during formation was largest near the center where densities are high (Kormendy & Sanders 1992). Dissipation favors disky distortions. At large radii, dissipationless violent relaxation favors triaxiality. So we expect that some ellipticals will be disky near the center and boxy at large radii. Mergers are another reason to expect a variety of structures. Nieto & Bender (1989) provide further discussion. Our classification is useful only if these complications are not too serious. Fortunately, most galaxies in B+89 were predominantly boxy or disky; 20% were called "irregular", but even these may be classifiable if a_4 is measured over a suitably restricted range of radii.

We also expect that some ellipticals are both boxy and disky at the *same* radius (Kormendy & Djorgovski 1989). Accretion happens to all ellipticals, including ones that are anisotropic. Any accreted gas settles toward the center and into a principal plane. Frequently this is the equatorial plane. Star formation can then grow a disk inside an object that is otherwise anisotropic. The result would be an elliptical that is disky near the major axis and boxy elsewhere. This should not change our perception of its morphological type. Instead, we classify the galaxy according to its most clearcut properties and note any complications. This may not be possible for all objects.

Complications like these are an inevitable consequence of heterogeneous formation histories. We have to live with them. We cannot expect galaxies to be characterized by a single linear sequence of properties. The classification scheme of Fig. 1 is useful if it distills the most essential physics of elliptical galaxies. The flowering of this subject following the discovery of slow rotation shows how much our attention is focused on anisotropy. This is the motivation behind our proposed classification scheme.

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