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EXPLORATIONS IN HUBBLE SPACE: A QUANTITATIVE TUNING FORK

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ABSTRACT

In order to establish an objective framework for studying galaxy morphology, we have developed a quantitative two-parameter description of galactic structure that maps closely onto Hubble's original tuning fork. Any galaxy can be placed in this "Hubble space," where the x-coordinate measures position along the early-to-late sequence while the y-coordinate measures in a quantitative way the degree to which the galaxy is barred. The parameters defining Hubble space are sufficiently robust to allow the formation of Hubble's tuning fork to be mapped out to high redshifts. In the present paper, we describe a preliminary investigation of the distribution of local galaxies in Hubble space based on the CCD imaging atlas published by Frei et al. in 1996. We find that barred, weakly barred, and unbarred galaxies are remarkably well separated on this diagnostic diagram. The spiral sequence is clearly bimodal and indeed approximates a tuning fork: strongly barred and unbarred spirals do not simply constitute the extrema of a smooth unimodal distribution of bar strength but, rather, populate two parallel sequences. Strongly barred galaxies lie on a remarkably tight sequence, strongly suggesting the presence of an underlying unifying physical process. Rather surprisingly, weakly barred systems do not seem to correspond to objects bridging the parameter space between unbarred and strongly barred galaxies but, instead, form an extension of the regular spiral sequence. This relation lends support to models in which the bulges of late-type spirals originate from secular processes driven by bars.

Key words: galaxies: evolution — galaxies: fundamental parameters

1. INTRODUCTION

In any branch of science, classification systems work best when applied to subsets of objects that are unambiguously distinct. In such cases, a meaningful classification system can lead to fundamental insights. Two obvious examples are Mendeleev's organization of chemical data into the periodic table of the elements, a discovery that anticipated electron orbital structure by decades, and Linnean binary nomenclature, which has formed the basis of the scientific naming scheme applied to organisms for over two centuries and which lies at the foundation of most studies of evolution and natural selection.

On the other hand, the division of a smoothly varying population into subjectively defined classes has always proved a "sure formula for endless bickering among specialists, for no two will ever agree" (Gould 1998, p. 96). On this basis, it seems reasonable to ask whether a truly fundamental classification scheme for galaxies will ever be devised, because unlike systems whose components are either perfectly discrete or of roughly uniform strength, galaxy properties span a broad continuum. In addition, the complexity of galaxies' morphologies means that any classification is likely to be based on a rather complex mixture of properties rather than a single defining feature. For such systems it may be more meaningful to think in terms of distributions in a multidimensional parameter space rather than in terms of discrete classes (Abraham et al. 1994; Bershady, Jangren, & Conselice 2000; van den Bergh et al. 2000).

Despite these caveats, Hubble's (1926) simple scheme for classifying galaxy morphology has proved remarkably versatile and robust. Hubble classified galaxies into ellipticals and spirals, defining a sequence from "early" to "late" types[1] by the size of the central bulge and the smoothness and pitch angle of the spiral arms, using the letters *a* to *c* to designate the location along the sequence. He then further divided the spiral galaxies into two parallel sequences of barred ("'SB") and unbarred ("S") galaxies, depending on whether the central region contained a strong non-axisymmetric distortion. Drawing the full sequence from elliptical galaxies to late-type spiral galaxies, with the spiral sequence bifurcating into parallel barred and unbarred sequences, one obtains the classical "tuning fork" scheme for classifying galaxy morphology. The catchall category of "irregular" allows one to deal with galaxies that do not fit within this simple scheme, but in the nearby universe, the vast majority of bright galaxies can be fairly reliably placed somewhere on the tuning fork.

In the past decade, a number of factors have arisen that drive us to look beyond such a qualitative scheme. Imaging surveys encompassing millions of galaxies, such as the Sloan Digital Sky Survey (SDSS), are now sufficiently large that visual classification is impractical. Furthermore, direct studies of galaxy evolution are now possible by imaging galaxies at high redshift using the *Hubble Space Telescope* (*HST*). However, with the notable exception of data from the Hubble Deep Field (Williams et al. 1996), *HST* images of distant galaxies are not of high enough quality for it to be possible to undertake traditional morphological classi-

[1] It is commonly held that Hubble used this nomenclature because he believed that the galaxies formed a temporal sequence. In fact, he explicitly warns against interpreting his choice of adjective in this way (Hubble 1926, p. 326).

fications directly onto Hubble's tuning fork, since the finer details of spiral structure cannot be robustly studied at the signal-to-noise levels typical of these data.

To get around this difficulty, the morphologies of distant galaxies have been probed using several different techniques, including

1. Visual classifications using coarse bins that neglect the visibility of spiral structure (Griffiths et al. 1994; Glazebrook et al. 1995; Driver, Windhorst, & Griffiths 1995; van den Bergh et al. 1996);
2. Classifications based on surface brightness profile fits to analytical models (Schade et al 1995; Odewahn et al 1997; Phillips et al. 1997; Marleau & Simard 1998; Corbin et al. 2000);
3. More general automated schemes based on various combinations of image concentration and surface brightness (Abraham et al. 1994), image concentration and asymmetry (Abraham et al. 1996a; Brinchmann et al. 1998; Volonteri, Saracco, & Chincarini 2000), and image concentration, asymmetry, surface brightness, and spectral class (Bershady et al. 2000).

Analysis using such techniques places the epoch at which the general framework of the early-to-late sequence is established to be at a redshift of $z \sim 1$ (Brinchmann et al. 1998; Driver et al. 1998).

Evidence for even more recent evolution in Hubble's tuning fork has come from studies of the fraction of barred galaxies as a function of redshift. Unlike other aspects of spiral structure, bars are fairly high surface brightness features and are visible to quite high redshifts. Van den Bergh et al. (1996) noted that the data from the Hubble Deep Field (North) gave the visual impression that there are few barred galaxies at high redshift. A quantitative analysis of both Hubble Deep Fields by Abraham et al. (1999) confirmed this visual impression and showed that barred galaxies are rare at redshifts beyond $z \sim 0.5$. Recent data from the Caltech Faint Galaxy Redshift Survey have lent further support to this picture (van den Bergh et al. 2000).

A major stumbling block in characterizing the evaporation of the Hubble sequence as a function of redshift has been the absence of a quantitative framework for describing the classical tuning fork. The primary aim of this paper is to set such a framework. Any galaxy can be placed in this "Hubble space," where the x-coordinate measures position along the early-to-late sequence while the y-coordinate measures in a quantitative way the degree to which the galaxy is barred. Since this system is fully parametric, it is not keyed in any way to local archetypes, and the system is robust enough to be useful over a broad range of redshifts.

The second aim of this paper is to apply this quantitative analysis to the morphological classification of nearby galaxies. Specifically, we seek to determine whether a tuning-fork–shaped distribution genuinely defines the local "morphological zero point" or whether Hubble's classification scheme is only a convenient idealization. The bifurcation implied by the tuning-fork paradigm itself implies a genuine distinction between barred and unbarred galaxies. It is therefore important to determine whether a bimodal distribution of barred and unbarred galaxies exists in Hubble space or whether these objects are better described as corresponding to the tails of a unimodal distribution, with the "average" galaxy lying somewhere in the middle. In addition to providing a baseline against which the properties of distant galaxies can be compared, this analysis may also offer insights into the physical interpretation of Hubble's original classification scheme.

The remainder of this paper is arranged as follows: In § 2, we present the two quantities adopted to parameterize Hubble space. In § 3, we make a preliminary exploration of Hubble space using the data from the Frei et al. (1996) atlas. The limitations of this sample for conducting this investigation are also discussed. The implications of this analysis are discussed in § 4, and our conclusions are summarized in § 5.

2. DEFINITION OF HUBBLE SPACE

2.1. *Measuring Hubble Stage*

As described above, the classical Hubble type of a galaxy is based on the visual impression of several aspects of the system's properties. The compound nature of this classification scheme is not conducive to summarizing a galaxy's morphology with a single quantitative parameter. However, the close correlation between the parameters defining the Hubble type means that one can obtain a remarkably good measure of position on the early-to-late sequence (the "Hubble stage" as defined in the Third Reference Catalog of Bright Galaxies [RC3; de Vaucouleurs et al. 1991]) by focusing on a single parameter, namely, the bulge-to-disk ratio of the galaxy. We therefore measure the location of galaxies along the early-to-late axis of Hubble space using the central concentration parameter, C, defined in Abraham et al. (1994) and closely related to the parameter defined by Doi, Fukugita, & Okamura (1993). This quantity tracks bulge-to-disk ratios very closely and has been shown to provide a good quantitative substitute for more orthodox visual classifications (Abraham et al. 1996b).

2.2. *Measuring Bar Strength*

A first attempt at robustly measuring the orthogonal ordinate in Hubble space, the bar strength, was made by Abraham et al. (1999). Their parameter, $(b/a)_{\rm bar}$, measured the intrinsic axis ratio of any central bar under the assumption that the distribution of light corresponds to a thin disk that is intrinsically axisymmetric at large radii. This model is clearly an idealization but still provides a robust objective measure of bar strength irrespective of the true distribution of light in the galaxy. As noted by Abraham et al. (1999), the assumption of a two-dimensional disk clearly becomes unreasonable if a galaxy is viewed close to edge-on, when the three-dimensional shape of the central bulge becomes a prominent feature. However, it is intrinsically almost impossible to determine whether a galaxy that lies close to edge-on is barred on the basis of photometry alone. We therefore follow Abraham et al. (1999) and only attempt to determine the value of $(b/a)_{\rm bar}$ for galaxies whose axial ratios imply an inclination $i < 60°$.

Abraham et al. (1999) calculated $(b/a)_{\rm bar}$ using the second-order moments obtained by slicing a galaxy image at two intensity levels. The moments at these slices were used to define "inner" and "outer" ellipses, whose axis ratios and orientations were used to calculate $(b/a)_{\rm bar}$. A deficiency of this technique is the rather ad hoc choice of intensity levels used to define these ellipses (10% and 85% of the image maximum after the top 2% of the image pixels had been clipped), since it is conceivable that barred systems could exist with isophotal signatures outside the range explored by these cuts. To remedy this deficiency, we adopt here a "multithresholding" approach to define the optimum intensity cuts, using the following procedure: A single outer ellipse is defined using second-order moments obtained by a 3 σ cut above the sky noise, σ. A succession of inner ellipses is then defined by slicing the galaxy image at a range of intensity levels spaced apart by 1 σ. At each cut, only those pixels contiguous with the center of the galaxy (defined as the position of the pixel with maximum flux) are retained. Some portions of a galaxy will be poorly described by elliptical isophotes, either intrinsically or because of poor sampling near the center of the object. Therefore, ellipses encompassing fewer than 80% of the pixels contained within the original isophote are discarded, as are ellipses with semimajor-axis lengths smaller than 5% of the radius of the outer isophote. For every remaining ellipse, $(b/a)_{\rm bar}$ is calculated using equation (2) of Abraham et al. (1999). The final value of $(b/a)_{\rm bar}$ adopted for the galaxy is the minimum value of $(b/a)_{\rm bar}$ over all slices, which therefore defines the maximum of any barlike distortion in the galaxy.

As a further refinement, we then calculate a quantity that is more closely related to most morphologists' subjective notion of bar strength. Specifically, we define

$$f_{\rm bar} = \frac{2}{\pi}\left[\arctan\,(b/a)_{\rm bar}^{-1/2} - \arctan\,(b/a)_{\rm bar}^{-1/2}\right] . \qquad (1)$$

This parameterization maps the bar strength into a closed interval from zero (unbarred) to unity (infinitely strong bar). For an idealized picture of a galaxy containing a central elliptical bar of uniform surface brightness, this quantity is the minimum fraction of the bar's stars that one would have to rearrange to transform the structure into an axisymmetric distribution. As discussed above, we are not arguing that such an idealized model represents a real galaxy in any sense; rather, this explanation is intended to give a physical insight into the interpretation of the parameter, which remains valid for real systems.

3. THE DISTRIBUTION OF GALAXIES IN HUBBLE SPACE

Having defined the physical measure of Hubble space, we are now in a position to see how it is populated by galaxies. In this preliminary investigation, we will analyze the sample of nearby galaxies from the Frei et al. (1996) CCD imaging atlas. Of the 113 galaxies in the atlas, 91 are spirals, 56 of which satisfy the inclination cut of $i < 60°$. The CCD images in the Frei et al. sample were obtained using two telescopes (the Palomar 1.5 m and the Lowell 1.1 m) using different filters. Since the local morphological distribution has been defined using blue-sensitive photographic plates, in the present analysis we adopt the bluest images available for each object in the atlas (B_J-band images for data obtained at Lowell, and Gunn g images for observations from Palomar).

It is important to emphasize that the Frei et al. (1996) atlas was not designed to represent a flux-limited sample of objects: its original purpose was to provide a useful "training set" of galaxies for automated classification in the SDSS. It is clear that large homogeneous digital surveys such as the SDSS will ultimately provide the best way forward to the overall goal of understanding the distribution of galaxy morphologies in the universe. However, we will now show that the Frei et al. (1996) sample can already be used to draw several fairly general conclusions regarding the distribution of galaxies in Hubble space.

Figure 1 compares the distribution of morphological classifications for all low inclination $B < 13.5$ mag galaxies in the RC3, along with classifications for the corresponding low-inclination Frei et al. (1996) subsample. Individual histograms for the various bar classes from the RC3 are shown. Here we adopt the terminology of the RC3, which denotes strongly barred spirals as class SB, weakly or tentatively barred systems as class SAB, and unbarred spirals as class SA, with lowercase roman letters suffixed to denote Hubble stage. Clearly, the Frei et al. (1996) sample is strongly biased against early-type disk systems (S0 galaxies and Sa spirals), as well as very late-type spirals (Sd and beyond). Some galaxies near these end points are included in the Frei sample, but some bar classes are missing: strongly barred SBab galaxies are absent from the sample, while all Scd galaxies in the sample are weakly barred SABcd systems.

Fortunately, the Frei et al. (1996) sample is most representative (both in terms of relative numbers of systems as a function of Hubble stage and in terms of the mix of SA, SAB, and SB systems) for the intermediate- to late-type spirals (types Sb, Sbc, and Sc) that define the two arms of the original tuning fork. While the absolute number (~ 50) of such systems is not large, it is certainly comparable to the total number of archetypal galaxies that define the visual classification sequence. Thus, the Frei et al. (1996) sample, while modest in size, is actually a rather useful probe of the bifurcation of intermediate-to-late spiral galaxies into barred and unbarred systems, though it must be used with caution when probing early-type and very late-type spirals.

Figure 2 illustrates the inner and outer ellipses determined for three representative barred spirals in this sample using the multithresholding technique described above. These objects are illustrative of the general success of the multithresholding technique in isolating galactic bars over a broad range of intensity and size. The orientation and semimajor-axis length of the bar is determined very robustly by this technique. On the whole, bar axial ratios are also well constrained, although they tend to be somewhat underestimated for early-type systems, because the contribution from a strong central bulge tends to fatten inner isophotes and make bars less well defined. In fact, a similar effect also impacts visual classifications, as is clearly seen in Figure 1—note the sharp increase in the proportion of systems in the RC3 with unknown bar classifications as one moves from late-type to early-type galaxies.

The distribution of this sample in Hubble space is shown in Figure 3. Small "postage stamp" images of the individual galaxies denote the position of each object in parameter space, while the surrounding colored boxes divide the galaxy population into SA (*red*), SAB (*green*), and SB (*blue*) spirals. For comparison, this figure also shows the Hubble-space positions of the elliptical galaxies in the Frei et al. (1996) sample surrounded by black boxes.

Several points are evident from inspection of Figure 3:

1. Barred, weakly barred, and unbarred galaxies are remarkably well separated in the diagram. The quantitative parameters defining Hubble space are clearly rather closely related to the subjective criteria upon which the original tuning-fork classification system was based. There is no intermixing of unbarred galaxies and strongly barred galaxies, and only a small amount of intermixing between strongly barred and weakly barred galaxies. A close inspection of the individual galaxy images shown in Figure 3 suggests that even this small amount of mixing may well be

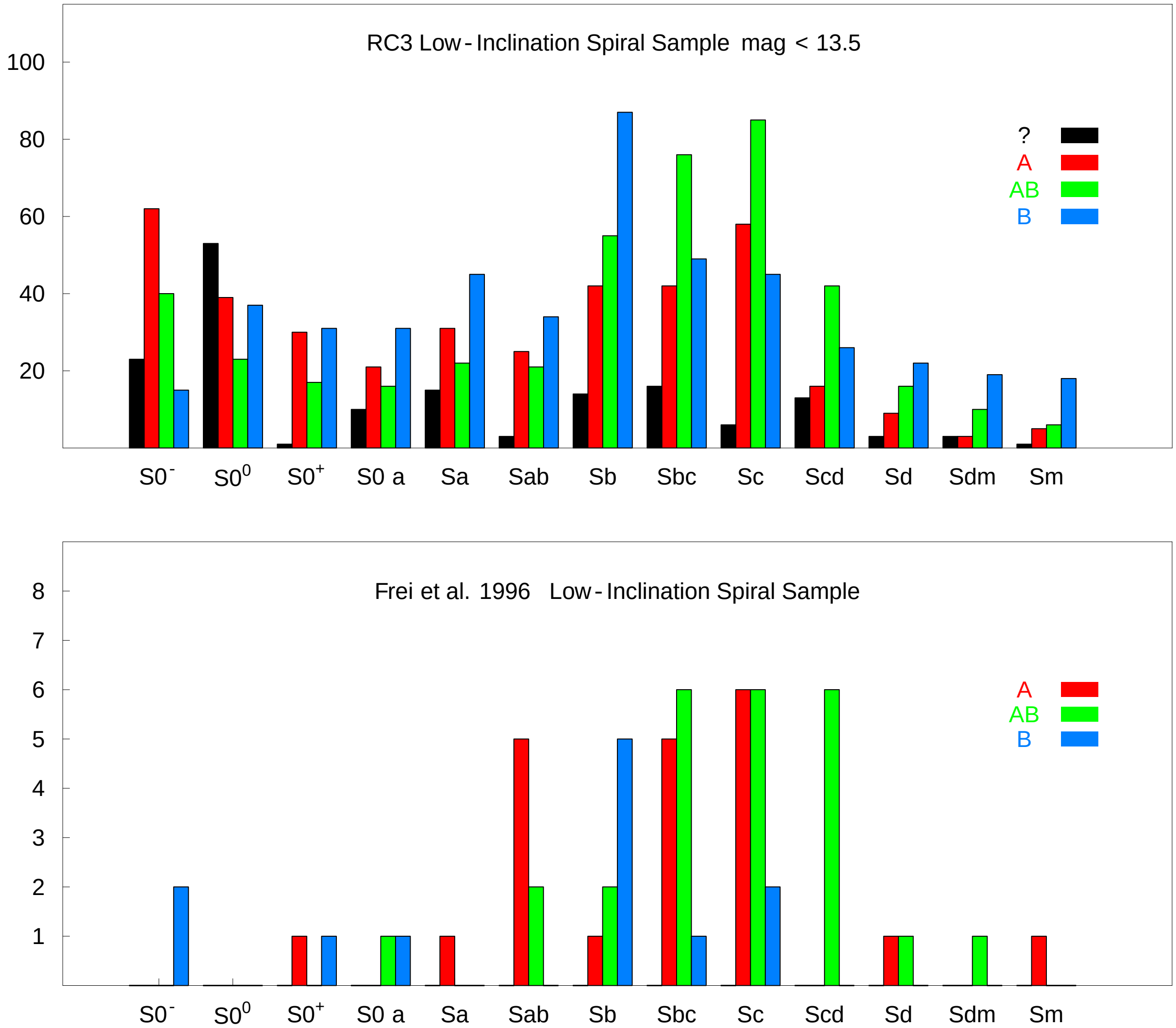

FIG. 1.—Distributions of unbarred (*red*), weakly barred (*green*), and strongly barred (*blue*) galaxies in the RC3 (*top*) and in the Frei et al. (1996) atlas (*bottom*). Numbers of galaxies are shown as a function of Hubble stage. All distributions correspond to systems with inclinations less than 60°, as inferred from their axial ratios. The RC3 sample was also cut at a magnitude limit of $B = 13.5$. Fainter than this limit, unclassified systems (*black*) begin to dominate the trends.

due to visual misclassification. The single elliptical galaxy scattered into the SB distribution is the result of an image defect (a slight ramp in the sky background).

2. There is a general broad correlation between C and $f_{\rm bar}$. This trend presumably just reflects the diluting effects of large bulges on quantitative measures of bar strength discussed above.

3. The spiral sequence is clearly bimodal. This bimodality is better displayed in Figure 4, which shows the distribution of spiral galaxies in Figure 3 projected onto an axis perpendicular to the mean correlation between C and $f_{\rm bar}$. Strongly barred spirals do not simply constitute the boundaries of a smooth unimodal distribution of bar strength. Instead, barred and unbarred spirals appear to populate two parallel sequences, with remarkably few galaxies occupying the region in between. It would be useful to assess the formal significance of the bimodality apparent in Figure 4, using, for example, the KMM test (Ashman, Bird, & Zepf 1994). However, there are two reasons why such a test would not yet be appropriate. First, this distribution was derived by projecting Figure 3 along the axis that maximizes the bimodality signal, and this maximization would not be accounted for in the significance of the test. Second, the current data set has folded in with it the selection that Frei et al. made in defining their sample, and we have no way of quantitatively assessing the impact of this selection on the shape of this distribution. Nonetheless, it will be important to carry out such a test when a larger, more objectively defined sample becomes available.

4. Rather surprisingly, weakly barred systems do not, on the whole, seem to correspond to systems bridging the parameter space between unbarred and strongly barred galaxies. Weakly barred SAB galaxies seem to be an extension of the SA sequence.

4. DISCUSSION

A schematic overview of Hubble space is presented in Figure 5, which shows where various classes of galaxies lie in this morphological parameterization. Colored rectangles on this diagram correspond to approximate "1 σ" contours in parameter space for the various populations. The dashed line intersecting these regions gives a schematic representa-

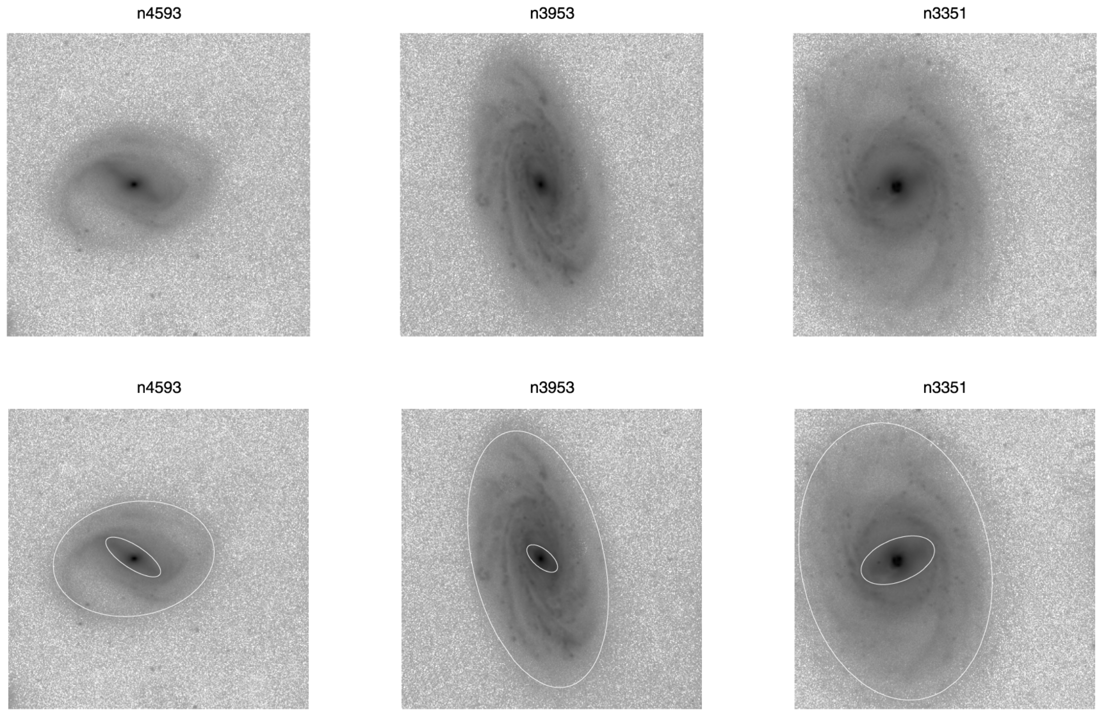

FIG. 2.—*Top*, representative SB galaxies from the sample of Frei et al. (1996);. *bottom*, the same galaxies shown with superposed inner and outer ellipses defined using the procedure described in the text.

tion of the classical tuning fork within this parameter space. What is most remarkable about this diagram is how apt Hubble's tuning-fork description remains almost 75 years after its introduction. The correspondence is not perfect: in Hubble space, the tuning fork is both skewed and horizontally flipped relative to its usual representation, and elliptical galaxies are not arrayed in a sequence of axial ratio. However, the bimodal distribution of galaxies is clearly rather more than a convenient textbook abstraction of a smooth continuum in the bar strength of galaxies. There really is a genuine bifurcation in the properties of galaxies, which cleanly divides barred and weakly barred/unbarred galaxies. The fact that SB galaxies lie on a remarkably sharply defined sequence strongly suggests the presence of some underlying unifying physical process—perhaps the classical bar instability (Binney & Tremaine 1987 and references therein).

The Frei et al. (1996) sample indicates that weakly barred SAB galaxies appear much more closely related to SA galaxies than to SB galaxies, with the SABs forming the late-type extension of the SA branch of the tuning fork. It is important to avoid overinterpreting this result, since it partially depends on the mix of later-type galaxies, for which, as we have discussed, the Frei sample is not entirely representative. Nonetheless, it seems quite possible that this will prove to be an example of a phenomenon that is obvious in a quantitative analysis but is difficult to detect using subjective criteria. Furthermore, it may well explain why the proportion of weakly barred systems is very discrepant in local catalogs. For example, there is reasonable agreement in local catalogs that the proportion of strongly barred galaxies is 25%–35%, based on the numbers given in the RC3, the Revised Shapley-Ames Catalog (RSA; Sandage & Tammann 1987), and the Uppsala General Catalogue (UGC; Nilson 1973). However, an additional 30% of spirals are classed as weakly barred in the RC3, substantially higher than in the UGC or RSA. Figure 5 suggests that this discrepancy is a manifestation of the nonfundamental nature of the "bars" seen in these objects, rendering them exceptionally problematic for visual pigeonholing.

Further support for the link between SAs and SABs can, in retrospect, be seen directly from the RC3 data. As Figure 1 shows, the fraction of SAB galaxies increases and the fraction of SA galaxies decreases as one goes along the Hubble sequence from S0 to Sd. Again, it is tempting to invoke a simple underlying physical process. Perhaps, for example, the small bulges and weak bars of the SAB galaxies are both the result of the bar-buckling instability seen in a number of numerical simulations (Combes & Sanders 1981; Raha et al. 1991; Pfenniger 1991). Such a process could well leave a modest nonaxisymmetric signature in what is essentially an unbarred galaxy, explaining the close relation of these systems to the SAs (Kormendy 1992).

Variations in the distribution of galaxies in Hubble space as a function of rest wavelength will be investigated in a future paper, but it seems likely that the distribution will be at least moderately wavelength dependent. Understanding the nature of this wavelength dependence will be important to extend our techniques for use in studying galaxies at higher redshifts. For example, Eskridge et al. (2000) found a higher fraction of barred galaxies when observing at longer wavelengths, which could produce a spurious decrease in the fraction of barred galaxies with redshift if one were to observe a sample of intrinsically identical galaxies through a single filter. Extending the methodology introduced in this paper to samples imaged at a range of wavelengths will allow direct comparison between the properties of nearby galaxies and those in higher redshift samples.

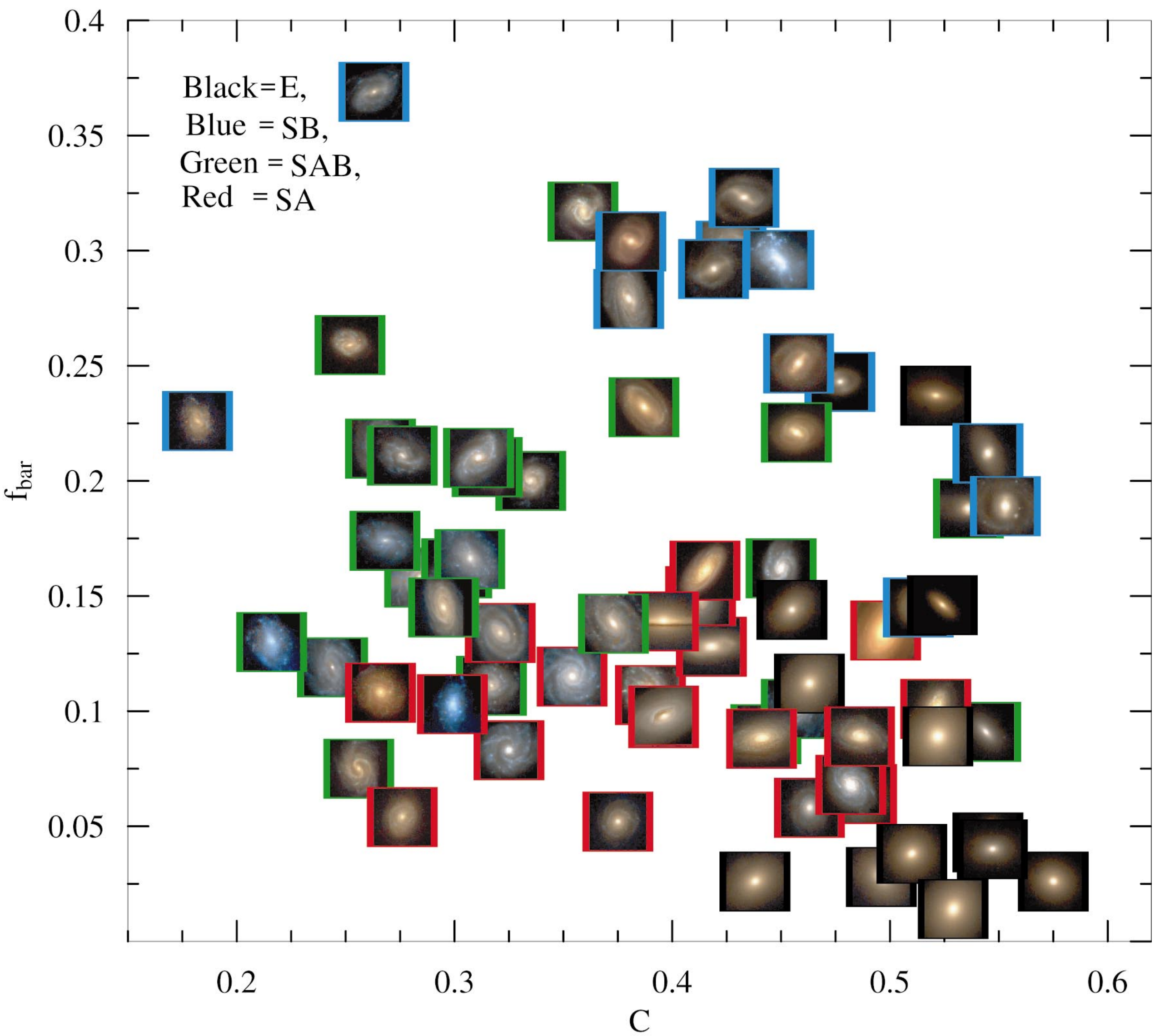

FIG. 3.—Distribution of the Frei et al. (1996) sample in Hubble space. "Postage stamp" images are shown at the position of each object in the diagram of central concentration vs. bar strength. Colored boxes subdivide the galaxy population into SA (*red*), SAB (*green*), and SB (*blue*) spirals. Elliptical galaxies are shown in black boxes.

5. CONCLUSIONS

Recent studies of high-redshift galaxies have revitalized the entire field of galaxy morphology. The myriad new forms of galaxies visible on deep *HST* images have led morphologists to devise new quantitative galaxy classification systems that, insofar as they connect to the classical Hubble system at all, focus on the early-to-late classification sequence and neglect the distinction between barred and unbarred galaxies. However, dynamical studies and direct observations of variations in the fraction of barred galaxies with redshift clearly imply that the bifurcation into barred and unbarred systems is a fundamental aspect of galaxy evolution.

In this paper, our goal has been to present a framework for combining these factors. We define a quantitative two-dimensional morphological parameterization ("Hubble space") that maps closely onto Hubble's original subjective visual definition of the morphological tuning fork. Using the Frei et al. (1996) sample, we have made a preliminary foray into Hubble space. We find that the distribution of bar strengths in galaxies in this sample is sharply bimodal—barred spirals do not simply delineate the extrema in a nearly uniform progression of galactic bar strength. Overall, this work lends support to Hubble's original picture, in which a genuine physical gulf exists between the properties of barred and regular galaxies and indicates that a natural division in parameter space can be used to distinguish barred from regular spirals objectively.

In addition, this work also shows how adopting a quantitative approach sheds light on a possible close link between regular and weakly barred spirals that is obscured by the nomenclature of visual classification. This analysis indicates that weakly barred systems may be naturally viewed as an extension of the regular spiral sequence rather than as bridges between strongly barred and regular spiral systems. This conclusion is based on a small sample of galaxies, however, and the relationship between various categories of barred spiral galaxies clearly needs to be investigated in a

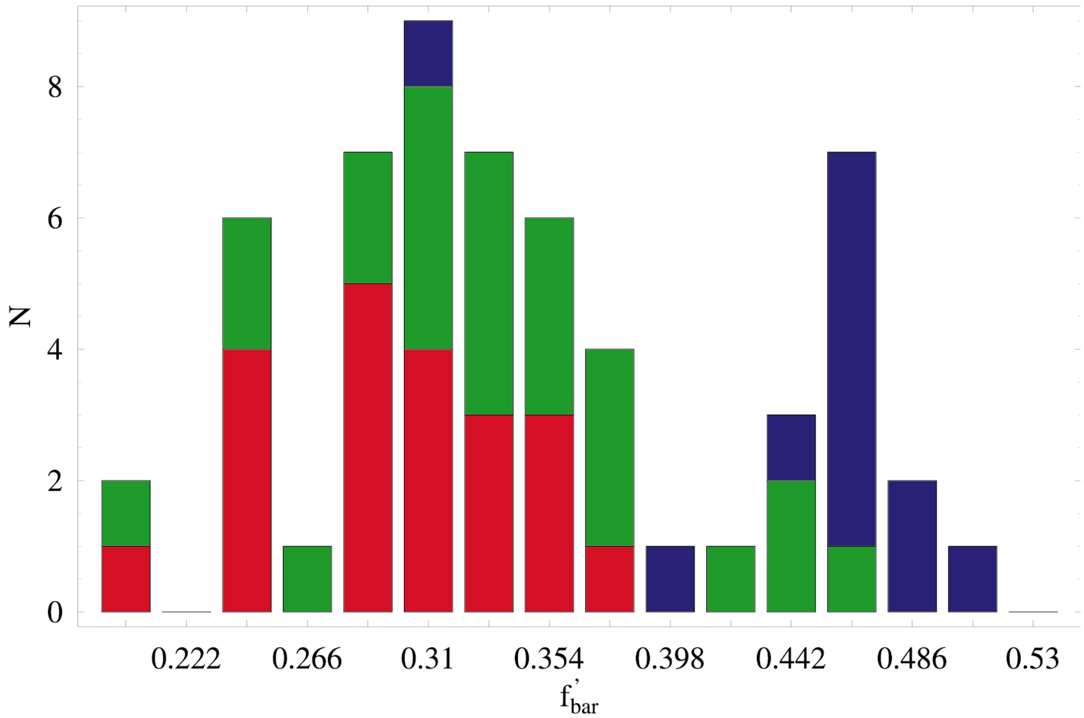

FIG. 4.—Histogram showing the distribution of spiral galaxies perpendicular to the sequences in Fig. 3. The color coding is the same as in Fig. 3. The histogram was calculated by rotating the distribution clockwise 60° about the point (0.4, 0.2) and then projecting it onto the x-axis.

more thorough manner with a much larger, more suitably selected sample. In any case, the rich variety of galaxy forms visible on deep *HST* images shows that the parameters defining Hubble space are insufficient, on their own, to fully encompass galaxy morphologies at high redshifts. Nevertheless, this investigation demonstrates that parametric measures of bar strength should certainly be incorporated into whatever successor to Hubble's sequence is ultimately adopted in order to describe galaxy morphologies over a broad range of look-back times.

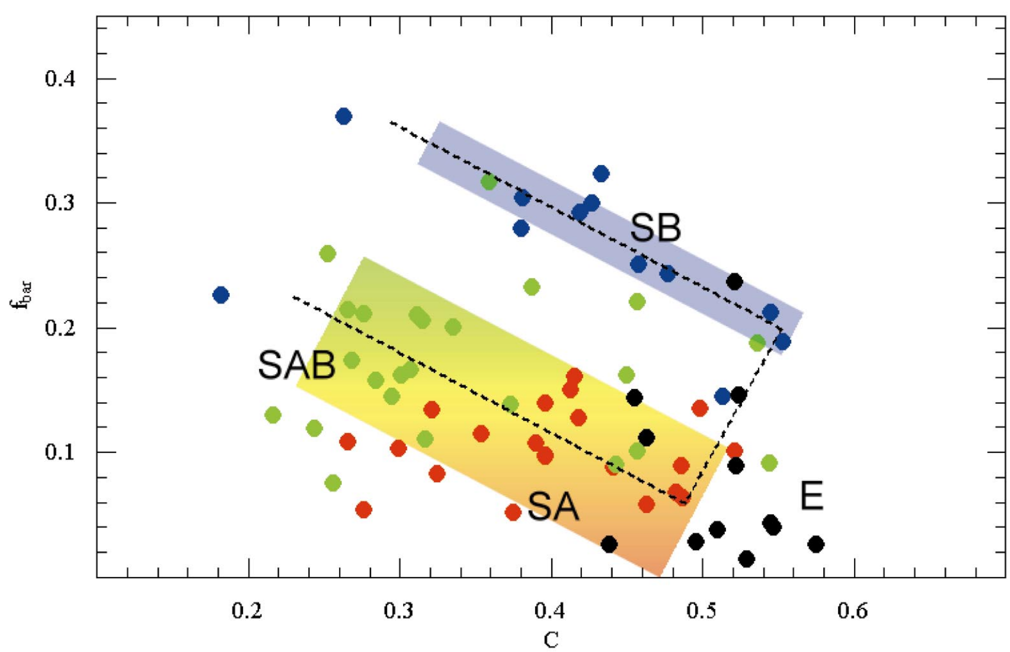

FIG. 5.—Distribution of galaxies shown in Fig. 3. Unbarred galaxies are shown in red, weakly barred galaxies are shown in green, strongly barred systems are shown in blue, and elliptical galaxies are shown in black. The dashed line indicates a schematic tuning fork. Shaded regions in the figure correspond to 1 σ rectangular contours delineating the two tines of the quantitative tuning fork.

Hubble constructed his original tuning fork guided strongly by his intuition and experience, but knowing comparatively little about the dynamical construction of galaxies. Seventy-five years later, Hubble's intuition stands vindicated, with the broad outline of his tuning fork holding up remarkably well to quantitative inspection.

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