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A NEAR-INFRARED PHOTOMETRIC PLANE FOR ELLIPTICAL GALAXIES AND BULGES OF SPIRAL GALAXIES

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ABSTRACT

We report the existence of a single plane in the space of global photometric parameters describing elliptical galaxies and the bulges of early-type spiral galaxies. The three parameters that define the plane are obtained by fitting the Sersic form to the brightness distribution obtained from near-infrared *K*-band images. We find, from the range covered by their shape parameters, that the elliptical galaxies form a more homogeneous population than the bulges. Known correlations like the Kormendy relation are projections of the photometric plane. The existence of the plane has interesting implications for bulge formation models.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: fundamental parameters — galaxies: spiral — galaxies: structure — infrared: galaxies

1. INTRODUCTION

Among the most important issues in studying the formation of galaxies are the epoch and physical mechanism of bulge formation. There are two competing scenarios for the formation of bulges. One assumes that the bulge and disk form independently, with the bulge preceding the disk (e.g., Andredakis, Peletier, & Balcells 1995, hereafter APB95), while the other suggests that the disk forms first and the bulge emerges from it later by secular evolution (Courteau, de Jong, & Broeils 1996). However, recent analysis of a complete sample of early-type disk galaxies (Khosroshahi, Wadadekar, & Kembhavi 2000, hereafter KWK) has shown that more than one mechanism of bulge formation may be at work. This is corroborated by recent *Hubble Space Telescope* observations, which show that distinct bulge formation mechanisms operate for large and small bulges.

Recent studies have revealed that the bulges of *early*-type disk galaxies are old (Peletier et al. 1999). This is in agreement with semianalytical results which claim that the bulges of field as well as cluster disk galaxies are as old as giant elliptical galaxies in clusters (Baugh et al. 1998). However, the formation mechanism of the bulges of *late*-type spiral galaxies is likely to be very different. For example, Carollo (1999) found that although a small bulge may form at early epochs, it is later fed by gas flowing into the galaxy core, possibly along a barlike structure caused by instabilities in the surrounding disk. The situation becomes more complicated for intermediate-sized bulges, with some having formed at early epochs and some relatively recently from gas inflows.

Correlations among global photometric parameters that characterize the bulge—such as colors, scale lengths, etc.—can be used to differentiate between the competing bulge formation models. These have the advantage of being independent of spectroscopic parameters, such as velocity dispersion, which are difficult to measure for bulges. Some of the photometric parameters such as color are measured directly, while others such as scale length require elaborate bulge-disk decomposition using empirical models for the bulge and disk profiles. Conventionally, radial profiles of bulges (de Vaucouleurs 1959), like those of elliptical galaxies (de Vaucouleurs 1948), have been modeled by the $r^{1/4}$ law. These are fully described by two parameters determined from the best-fit model—the central surface brightness $\mu_b(0)$ and an effective radius r_e, within which half the total light of the galaxy is contained. In recent years an additional parameter has been introduced, with the $r^{1/4}$ law replaced by an $r^{1/n}$ law (Sersic 1968), where n is a free parameter (e.g., Caon et al. 1993; APB95; KWK). The so-called Sersic shape parameter n is well correlated with other observables like luminosity, effective radius, bulge-to-disk luminosity ratio, and morphological type (APB95). In particular, it has been demonstrated that a tight correlation exists between $\log n$, $\log r_e$, and $\mu_b(0)$ (KWK).

In this Letter, we show that $\log n$, $\log r_e$, and $\mu_b(0)$ for elliptical galaxies are tightly distributed about a plane in logarithmic space and that this *photometric plane* for elliptical galaxies is indistinguishable from the analogous plane for the bulges of early-type disk galaxies. Throughout this Letter, we use $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

2. THE DATA AND DECOMPOSITION METHOD

The analysis in this study is based on the near-IR, *K*-band images of 42 elliptical galaxies in the Coma cluster (Mobasher et al. 1999). This is combined with a complete magnitude- and diameter-limited sample of 26 early-type disk galaxies in the field (Peletier & Balcells 1997) from the Uppsala General Catalogue (Nilson 1973). Details about the sample selection, observations, and data reduction are given in the above references. We chose to work with *K*-band images because the relative lack of absorption-related features in the band leads to smooth, featureless light profiles that are convenient for extraction of global parameters.

Extracting the global bulge parameters of a galaxy requires the separation of the observed light distribution into bulge and disk components. This is best done using a two-dimensional technique, which performs a χ^2 fit of the light profile model to the galaxy image. A scheme is used in which each pixel is weighted by its estimated signal-to-noise ratio (Wadadekar, Robbason, & Kembhavi 1999).

We decomposed all the galaxies in our sample into a bulge component which follows an $r^{1/n}$ law with

$$I_{\rm bulge}(r) = I_b(0)e^{-2.303b_n(r/r_e)^{1/n}}, \qquad (1)$$

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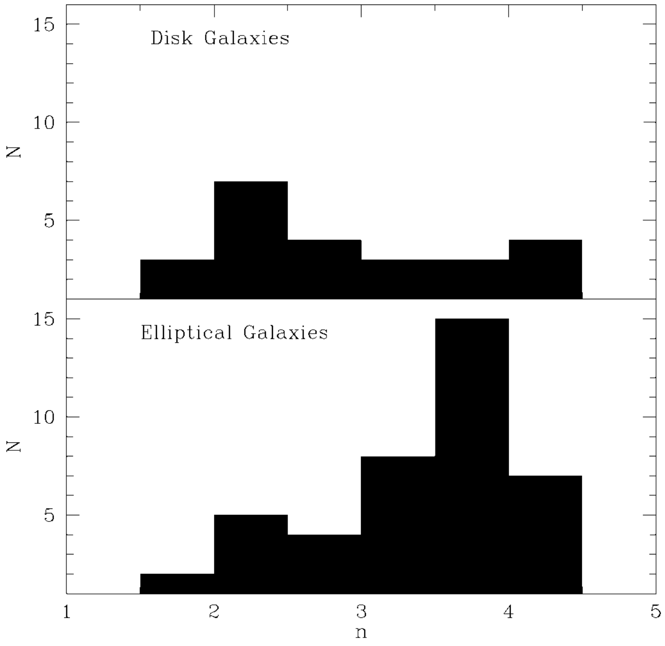

FIG. 1.—Histogram of the shape parameter *n* for bulges of disk galaxies and elliptical galaxies.

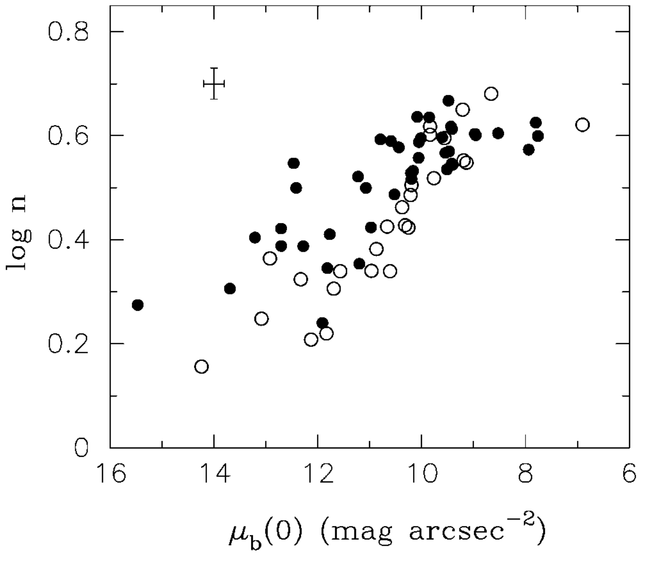

FIG. 2.—Logarithm of the shape parameter *n* plotted against the deconvolved bulge central surface brightness. The open circles represent bulges of disk galaxies, and the filled circles represent elliptical galaxies. Typical error bars are shown.

where $b_n = 0.8682n - 0.1405$ and r is the distance from the center along the major axis. The disk profile is taken to be an exponential $I_d(r) = I_d(0)e^{-(r/r_d)}$, where r_d is the disk scale length and $I_d(0)$ is the disk central intensity. Apart from the five parameters mentioned here, the fit also involves the bulge and disk ellipticities. The model for each galaxy was convolved with the appropriate point-spread function (PSF). Details of the procedure used in the decomposition of the disk galaxies are given in KWK. We have obtained good fits for all 42 of the 48 elliptical galaxies in the complete sample of Mobasher et al. (1999) for which we have data and for 26 of the 30 disk galaxies in the complete sample of APB95. Twelve of the 42 elliptical galaxies show a significant disk ($D/B \gtrsim 0.2$). Four disk galaxies did not provide good fits because of their complex morphology (see KWK), and these galaxies have been excluded from our discussion.

In Figure 1 we plot histograms showing the distribution of the shape parameter *n* for the two samples. For elliptical galaxies, *n* ranges from 1.7 to 4.7 with a clear peak around $n = 4$. This observation is in agreement with the fact that de Vaucouleurs' law has historically provided a reasonable fit to the radial profile of most (but not all) elliptical galaxies. For the disk galaxies, *n* ranges from 1.4 to 5 with an almost uniform distribution within this range. The rather flat distribution in *n* for the disk galaxies implies that de Vaucouleurs' law will provide a poor fit to the bulges of these galaxies. This is indeed the case as demonstrated in de Jong (1996).

3. THE PHOTOMETRIC PLANE

Study of the correlations among the parameters describing photometric properties of elliptical galaxies and bulges of spiral galaxies is essential in constraining galaxy formation scenarios. We find that for the spiral galaxies sample, the bulge central surface brightness is well correlated with log *n*, with a linear correlation coefficient of −0.88 (Fig. 2). The corresponding coefficient for the elliptical galaxies, also shown in Figure 2, is −0.79. These relations are significant at greater than the 99.99% level as measured by the Student's *t*-test. There is a weak correlation between bulge effective radius and *n* for the disk galaxies (KWK), but such a correlation does not exist for the elliptical galaxies.

An anticorrelation between the effective radius and mean surface brightness within the effective radius—known as the Kormendy relation (Kormendy 1977; Djorgovski & Davis 1987)—has been reported in elliptical galaxies. In Figure 3 we plot the mean surface brightness within the effective radius against effective radius for the two samples. The elliptical galaxies are clustered around the best-fit line: $\langle \mu_b(r_e) \rangle = 2.57 \log r_e + 14.07$ with an rms scatter of 0.59 in mean surface brightness. A weaker relation with larger scatter exists for the bulges of the early-type spiral galaxies, suggesting a formation history similar to that of elliptical galaxies. As we demonstrated

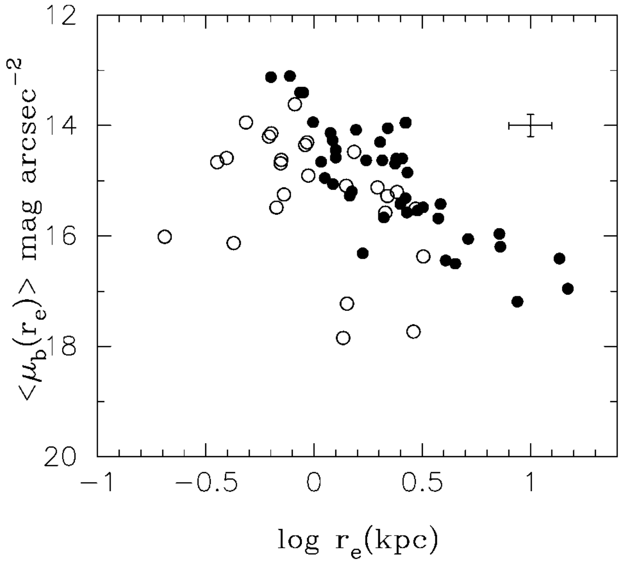

FIG. 3.—Kormendy relation for bulges of disk galaxies and elliptical galaxies. The filled circles represent elliptical galaxies, and the open circles represent bulges of disk galaxies. Typical error bars are shown.

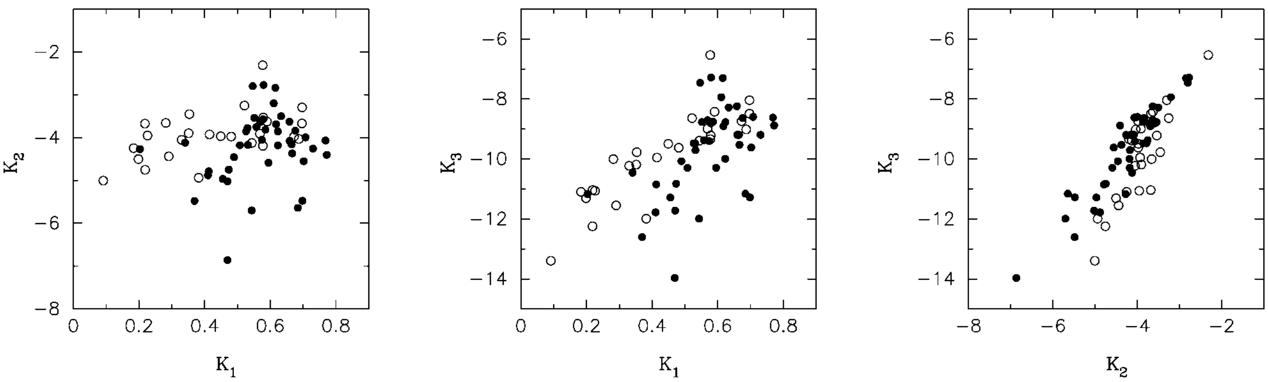

FIG. 4.—A face-on and two edge-on views of the *photometric plane*, where $\boldsymbol{K}_1 = 0.986 \log n + 0.169 \log r_e$, $\boldsymbol{K}_2 = 0.157 \log n - 0.916 \log r_e - 0.377\mu_b(0)$, and $\boldsymbol{K}_3 = -0.064 \log n + 0.372 \log r_e - 0.93\mu_b(0)$. The filled circles represent elliptical galaxies, and the open circles represent bulges of disk galaxies.

in KWK, the bulges of late-type spiral galaxies do *not* show a Kormendy-type relation, suggesting a different formation history.

It is possible that some of the scatter seen in the Kormendy relation is caused by the effect of a third parameter, which can only be n in our scheme. We have applied standard bivariate analysis techniques to obtain the best-fit plane in the space of the three parameters $\log n$, $\mu_b(0)$, and $\log r_e$. We find that the least scatter around the best-fit plane is obtained by expressing it in the form $\log n = A \log r_e + B\mu_b(0)$ + constant and minimizing the dispersion of $\log n$ as measured by a least-squares fit.

The equation of the best-fit plane for the elliptical galaxies is

$$\log n = (0.173 \pm 0.025) \log r_e - (0.069 \pm 0.007)\mu_b(0) + (1.18 \pm 0.05), \qquad (2)$$

while for the bulges of the disk galaxies it is

$$\log n = (0.130 \pm 0.040) \log r_e - (0.073 \pm 0.011)\mu_b(0) + (1.21 \pm 0.11). \qquad (3)$$

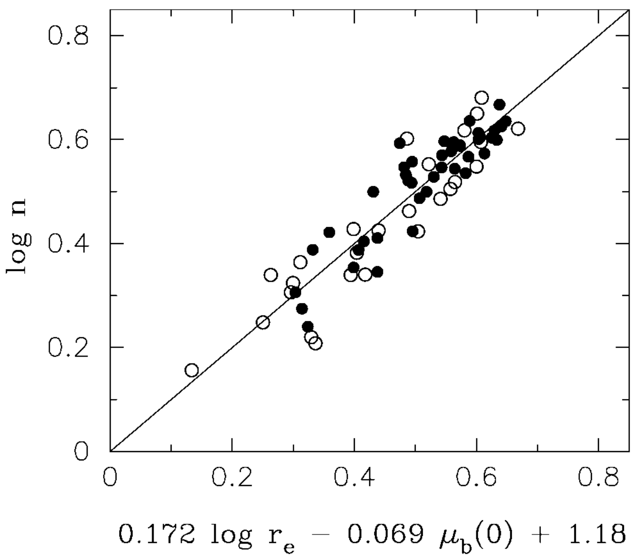

FIG. 5.—Tight representation of the best-fit *photometric plane*. The filled circles represent elliptical galaxies, and the open circles represent bulges of disk galaxies. The line is a plane fit to the data.

The errors in the best-fit coefficients here were obtained by fitting planes to synthetic data sets generated using the bootstrap method with random replacement (Fisher 1993). The scatter in $\log n$ for the above planes is 0.043 dex (corresponding to 0.108 mag) and 0.058 dex (corresponding to 0.145 mag), respectively.

The angle between the two planes is $2^{\circ}\!.41 \pm 1^{\circ}\!.99$; this error was also obtained by the bootstrap technique. The difference in angle between the two planes is only slightly more than the 1 σ uncertainty, which strongly suggests that the two planes are identical. We therefore obtained a new equation for the common plane, combining the data for the two samples, which is

$$\log n = (0.172 \pm 0.020) \log r_e - (0.069 \pm 0.004)\mu_b(0) + (1.18 \pm 0.04). \qquad (4)$$

The smaller errors here are due to the increased size of the combined sample.

A face-on and two mutually orthogonal edge-on views of the best-fit plane for the two samples are shown in Figure 4. $\boldsymbol{K}_1$, $\boldsymbol{K}_2$, and $\boldsymbol{K}_3$ are orthonormal vectors constructed from linear combinations of the parameters of the photometric plane. An additional representation of this best-fit plane with $\log n$ as the ordinate, together with the data points used in the fit, is shown in Figure 5. The rms scatter in $\log n$ here is 0.050 dex, corresponding to 0.125 mag. This is comparable to the rms error in the fitted values of $\log n$, so any intrinsic scatter about the plane is small.

It is possible that some of the observed correlation is produced due to correlations between the fitted parameters of the bulge-disk decomposition. We have examined the extent of such an induced correlation, using extensive simulations of model galaxies obtained using the observed distributions of n, $\mu_b(0)$, and r_e for both samples. We chose at random a large number of n, $\mu_b(0)$, and r_e triplets from these distributions, with the values in each triplet chosen independently of each other. Such a random selection ensured that there was no correlation between the input parameters. Other parameters needed to simulate a galaxy, like disk parameters, were also chosen at random from the range of observed values. We added noise at the appropriate level to the simulated images and convolved the models with a representative point-spread function. We then extracted the parameters for these galaxies using the same procedure as we adopted for the observed sample. Results from the fit to the simulated data do not show significant univariate or bivariate correlations between the extracted parameters. This indicates that the correlations seen in the real data are not generated by correlated errors.

4. DISCUSSION

It is tempting to investigate the use of equation (4) as a distance indicator. The main source of uncertainty here is that the two distance-independent parameters, log n and $\mu_b(0)$, are in fact correlated, leading to an increased error in the best-fit photometric plane and hence in the estimated log r_e values. This gives an error of 53% in the derived distance, which is similar to the error in other purely photometric distance indicators but is significantly larger than the ∼20% error found in distances from the near-IR fundamental plane, using both photometric and spectroscopic data (e.g., Mobasher et al. 1999; Pahre, Djorgovski, & de Carvalho 1998). However, data for the photometric plane are easy to obtain, as no spectroscopy is involved and it should be possible to get more accurate distances to clusters by independently measuring distances to several galaxies in the cluster.

The elliptical galaxies seem to form a more homogeneous population than the bulges of spiral galaxies, as revealed from the distribution of their shape parameter n. Considering that the near-infrared light measures the contribution from the old stellar population in galaxies (i.e., the integrated star formation) and since the near-infrared mass-to-luminosity ratio $(M/L)_K$ is expected to be constant among the galaxies, the relatively broad range covered by the shape parameter n for bulges of spiral galaxies reveals differences in the distribution of the old population among these bulges. Environmental factors could play an important role here, since the elliptical galaxies in our sample are members of the rich Coma cluster, while the spiral galaxies are either in the field or are members of small groups. While elliptical galaxies and bulges appear to be different in the context of the Kormendy relation, they are unified onto a single plane when allowing for differences in their light distribution, as measured by the shape parameter n. This supports the use of n as a fundamental parameter in studying elliptical galaxies and bulges of early-type disk galaxies, similar to the velocity dispersion in the fundamental plane of elliptical galaxies. The existence of a photometric plane for elliptical galaxies and bulges of early-type disk galaxies further supports an independent study by Peletier et al. (1999), which found that bulges in early-type disk galaxies and elliptical galaxies have similar stellar content and formation epochs. It will be important to see whether the photometric plane for lenticulars also coincides with the plane for elliptical galaxies and bulges of early-type galaxies in order to explore whether lenticulars indeed provide an evolutionary link between elliptical galaxies and early-type disk galaxies.

The observed tightness of the photometric plane provides a strong constraint on formation scenarios, and therefore it is necessary to study its physical basis. Recently Lima Neto, Gerbal, & Marquez (1999) have proposed that elliptical galaxies are stellar systems in a stage of quasi-equilibrium, which may in principle have a unique entropy per unit mass: the *specific entropy*. It is possible to compute the specific entropy assuming that elliptical galaxies behave as spherical, isotropic, one-component systems in hydrostatic equilibrium, obeying the ideal-gas equations of state. Using the specific entropy and an analytic approximation to the three-dimensional deprojection of the Sersic profile, they predict a relation between the three parameters of the Sersic law. This relation defines a plane in parameter space which they call the *entropic plane*. The parameters used in their fit are not identical to ours, and therefore a comparison is not straightforward.

The photometric plane may be useful in probing the bulge formation mechanism in galaxies. In this context it will be interesting to see whether the bulges of late-type disk galaxies also share a single plane with the bulges of early-type disk galaxies and elliptical galaxies. If they do, then a single mechanism for bulge formation in all types would be indicated. But if bulges in early- and late-type disk galaxies are formed differently (Peletier et al. 1999; Carollo 1999), then a single plane is not expected. It will also be of interest to compare scaling laws that follow from the photometric plane with those implied by the existence of the fundamental plane (Djorgovski & Davis 1987) of elliptical galaxies.

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