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THE NEAR-INFRARED PHOTOMETRIC PLANE OF GALAXIES

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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 which define the plane are obtained by fitting the Sersic form to the brightness distribution obtained from near-infrared K band images. Known correlations like the Kormendy relation are projections of this photometric plane. The existence of the plane may help constrain bulge formation models.

1 Introduction

Amongst the most important issues in studying 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 later from it 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 HST observations, which show that distinct bulge formation mechanisms operate for large and small bulges. Bulges of *early* type disk galaxies are old (Peletier et al. 1999) and may have a formation mechanism identical to that of elliptical galaxies. However, the formation mechanism of the bulges of *late* type disk galaxies is likely to be very different. For example, using HST data, 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 bar-like structure caused by instabilities in the surrounding disk.

Correlations among global photometric parameters that characterize the bulge – such as colors, scale lengths etc. – can be used to differentiate between 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 the colors are measured directly, while others like the scale lengths 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 $\mu_{\mathrm{b}}(0)$ 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 a $r^{1/n}$ law (originally proposed by Sersic 1968), where n is a free parameter (e.g. Caon et al. 1993, APB95, KWK). The Sersic shape parameter n is well correlated with other observables like luminosity, effective radius, the bulge-to-disk luminosity ratio and morphological type (APB95). In particular, it has been demonstrated that a tight correlation exists between $\log n$, $\log r_{\mathrm{e}}$ and $\mu_{\mathrm{b}}(0)$ (KWK).

In this paper we show that $\log n$, $\log r_{\mathrm{e}}$ and $\mu_{\mathrm{b}}(0)$ 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. We use $H_0 = 50\,\mathrm{km\,sec^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$ throughout.

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 was combined with a complete magnitude and diameter limited sample of 26 early type disk galaxies in the field (Peletier and Balcells 1997) from the Uppsala General Catalogue (Nilson 1973). 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 which 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 2-dimensional technique, which performs a χ^2 fit of the light profile model to the galaxy image. A scheme is used in which is pixel is weighted by its estimated signal-to-noise ratio (Wadadekar, Robbason and Kembhavi 1999).

We decomposed disk galaxies into a bulge component which follows a $r^{1/n}$ law with

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

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 $I_{\rm d}(r) = I_{\rm d}(0)e^{-(r/r_{\rm d})}$, where $r_{\rm d}$ is the disk scale length and $I_{\rm d}(0)$ is the disk central intensity. Apart from the five parameters mentioned here, the fit also involves the bulge and disk ellipticities. Details of the procedure used in the decomposition of the disk galaxies are given in KWK. We have got 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 in 26 of the 30 disk galaxies in the complete sample of APB95. The four other disk galaxies did not provide good fits because of their complex morphology (see KWK). We have used only the values from the good fits fits in this paper.

3 Correlations and 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 (Figure 1). The corresponding coefficient for the elliptical galaxies, also shown in Figure 1, is -0.79. These relations are significant at $> 99.99\%$ level. 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 anti-correlation 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 2 we plot effective mean surface brightness against effective radius for the two samples. The elliptical galaxies are clustered around the best fit line – $\langle\mu_{\rm b}(r_{\rm e})\rangle = 2.57\log r_{\rm e} + 14.07$ with rms scatter of 0.59 in mean surface brightness. A similar relation, albeit 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 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 $\log n$, $\mu_{\rm b}(0)$ and $\log r_{\rm e}$. We find that the least scatter around the best fit plane is obtained by expressing it in the form $\log n = A\log r_{\rm e} + B\mu_{\rm b}(0) + \text{constant}$, and minimizing the dispersion of $\log n$.

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

$$\log n = (0.173 \pm 0.025) \log r_{\rm e} - (0.069 \pm 0.007)\mu_{\rm b}(0) + (1.18 \pm 0.05), \tag{2}$$

while for the bulges of the disk galaxies it is

$$\log n = (0.130 \pm 0.040) \log r_{\rm e} - (0.073 \pm 0.011)\mu_{\rm b}(0) + (1.21 \pm 0.11). \tag{3}$$

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 magnitude) and 0.058 dex (corresponding to 0.145 magnitude) respectively.

We have shown in Figure 3 near face-on views of the separate best fit planes for the two samples. The angle between the two planes is 2.41 ± 1.99 deg; this error was also obtained by the bootstrap technique. The error in the angle is large enough to support the hypothesis 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:

$$\log n = (0.172 \pm 0.020) \log r_{\rm e} - (0.069 \pm 0.004)\mu_{\rm b}(0) + (1.18 \pm 0.04), \tag{4}$$

The smaller errors here are due to the increased size of the combined sample. The rms scatter in $\log n$ here is 0.050 dex, corresponding to 0.125 magnitude. This is comparable to the rms error in the fitted values of $\log n$, so any intrinsic scatter about the plane is small.

It seems possible that some of the observed correlation is produced due to correlations between errors in 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, $\mu_{\rm b}(0)$ and $r_{\rm e}$ for both samples. We chose at random a large number of n, $\mu_{\rm b}(0)$ and $r_{\rm e}$ 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 Some implications for galaxy formation scenarios

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 single plane also implies that the integrated star formation is amongst the most important parameters in dictating their observed properties. This is further supported by the independent study by Peletier et al. (1999).

The observed tightness of the photometric plane provides a strong constraint on formation scenarios, and therefore it is important 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 a 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. We shall provide a detailed interpretation of our plane in relation to theirs using a semi-analytic gravo-thermal approach in a future paper. It will also be of interest to compare scaling laws which follow from the photometric plane with those implied by the existence of the fundamental plane (Djorgovski & Davis 1987) of elliptical galaxies.

5 Future work

It would be interesting to study the photometric plane of galaxies in intermediate redshift clusters to test the predictions of various galaxy formation models. It will be important to see whether the photometric plane for lenticulars too coincides with the plane for elliptical galaxies and bulges of early type galaxies, to explore whether lenticulars indeed provide an evolutionary link between elliptical galaxies and early type spiral galaxies. These projects are now underway.

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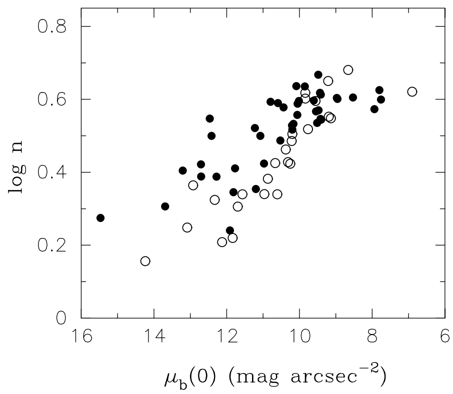

Figure 1: Logarithm of the shape parameter, n, is plotted against the unconvolved bulge central surface brightness. The open circles represent bulges of disk galaxies and the filled circles represent elliptical galaxies.

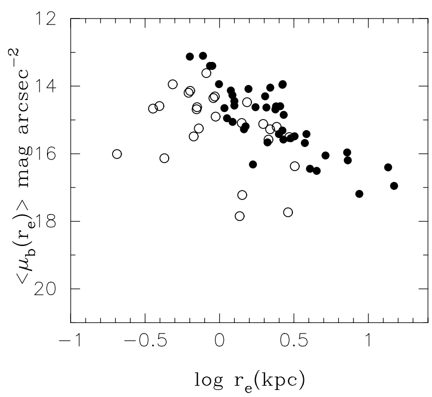

Figure 2: Kormendy relation for bulges of disk galaxies and elliptical galaxies. The filled circles represent elliptical galaxies and the open circles represent bulges of disk galaxies.

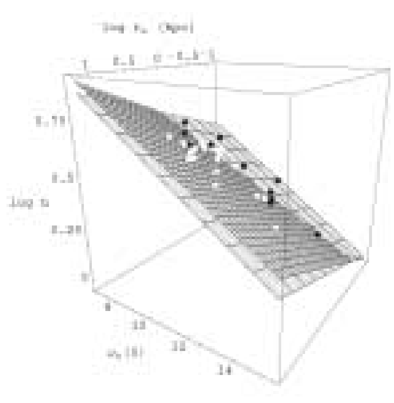

Figure 3: The best fit *photometric planes* for elliptical galaxies and bulges of disk galaxies. The fine gridded plane is for elliptical galaxies while the coarse gridded plane is for the disk galaxies. The data points are indicated by filled circles, the white circles are for elliptical galaxies and the black circles are for the bulges of disk galaxies. Data points lying below the planes are not visible.