**Abstract.** We determine the parameters of scaling relations analogous to the Fundamental Plane of elliptical galaxies for the bulges and disks of a sample of 40 spiral galaxies. To this end we derive structural parameters (scalelengths and surface brightnesses) from near infrared $H$ band images, and kinematical parameters (rotational velocities) from optical rotation curves. In the case of the disks, we test the accuracy of the derived relation as a distance indicator by comparing its scatter to that of the $H$ band Tully–Fisher relation for the same sample, and find that the accuracy attained by the latter is slightly higher (the dispersion is 19% versus 23% for this sample). It is speculated that the difference is due to the more robust character of global parameters, rather than those associated with the inner parts of disks. It also appears that (a) either the stellar mass-to-light ratios of bulge and disk increase with the size of the components, or (b) the bulge and disk relative contributions to the overall rotation of the galaxy (and, as a consequence, to its total mass) become steadily smaller with increasing size.

**Key words:** Galaxies: structure – fundamental parameters – distances and redshifts – Infrared: galaxies

1. Introduction

The existence of tight scaling relations between observable photometric and kinematic galaxy parameters, in particular the Fundamental Plane (FP) of elliptical galaxies (Jorgensen et al. 1996, Scodeggio 1997), and the Tully–Fisher relation for spirals (TF, Tully & Fisher 1977), finds its most straightforward application in the evaluation of galaxy distances. The small scatter observed in both relations implies a fine tuning between parameters strictly related to the stellar component alone, such as the optical luminosity, and the kinematic properties of the galaxy, which are affected by the overall mass distribution (both dark and visible). In the case of spiral galaxies, it is therefore suggestive that a tight scaling relation may also exist between photometric and kinematic properties of the disks alone, with a scatter as low as, or even lower, than the TF relation. Karachentsev (1989) found that, for a sample of 15 edge-on galaxy, the disk scale length $R_d$ was connected to the 21 cm line velocity width $W$ and the $I$–band central disk brightness $I(0)$ by the relation $R_d \propto W^{1.4}I(0)^{-0.74}$, with a scatter in $\log(R_d)$ of 0.048. The uncertainty implied in the distance is around 12%, smaller than the one usually achieved by the TF relation (15 ~ 20%). More recently Chiba & Yoshii (1995, CY95 hereafter) tested on a sample of 14 nearby spirals the relation

$$\log R_d = a \log(V_2I(0)^{-0.5}) + b$$  \hspace{1cm} (1)

in the $B$ band, where $V_2$ is the galaxy rotation velocity measured at 2.2 disk scalelengths. Since the contribution from the disk to the overall rotation curve (RC) has a maximum at this particular distance, the authors argue that the contributions from bulge and dark halo are likely to be less important, and therefore the measured velocity should represent a good estimate for the rotation of the disk alone. For a set of exponential disks of fixed mass-to-light ratio ($M/L$) one would expect $\log R_d \sim \log [V_2^2/I(0)]$, corresponding to $a = 2$ in Eq. (1). Actually CY95 find $a = 1.045$, again with a remarkably small scatter. On the other hand, recent work from Giovanelli (1997) suggests that the accuracy of Eq. (1) as a distance indicator is inferior to the one attained by the traditional TF relation by at least a factor of 2.

Besides being a tool to provide redshift-independent distances, scaling relations also contain information about how galaxies – and in particular their “visible” constituents – have formed and evolved (Gavazzi 1997, Ciotti 1997, Dalcanton et al. 1997, Burstein et al. 1997 – BBFN hereafter). In this respect, spiral disks are a potentially “easy” class of systems, since they are all characterized by well defined shape and kinematics: if the effects of extinction on their surface brightness distribution are accounted for, and a reliable estimate of their mass is obtained, the
information can be provided by the variation with wavelength of such properties, in particular by scaling relations involving colours (e.g., the colour magnitude relation; see Gavazzi 1993, Tully et al. 1998, Peletier & de Grijs 1998).

In this work we investigate the existence and tightness of a general scaling relation in the near infrared (NIR), similar to the one defining the FP, for both structural components (disks and bulges) of a sample of 40 nearby spiral galaxies. Our aim is to test the power of these relations as tools to measure galaxy distances, and use them to provide new information about the stellar content and star formation history of spiral galaxies. In the present paper we are going to deal mainly with the problem of the distance measurements, leaving a thorough discussion of the second point to future work. The use of NIR photometry is well suited for a study of this kind, since it minimizes the effect of internal extinction, and provides a good tracing of the stellar mass. In most cases, high resolution, optical RC’s allow us to trace the gravitational potential of the galaxies up to their innermost regions.

The photometric parameters are obtained, in the NIR $H$ band, from a bi-dimensional decomposition of the galaxy images, as described in Sect. 3. In Sect. 3 we show how the kinematical information are extracted from the galaxy RC’s, to which we fit a model composed by bulge, disk, and a dark halo. We subsequently derive the coefficients of the FP for bulges and disks, and compare the potential accuracy in a distance determination achieved by the disks’ relation to the one we obtain using the TF relation for the same sample. We finally investigate the trends of $M/L$’s with luminosity and galaxy size. Throughout the paper we adopt a Hubble constant $H_o = 75$ km s$^{-1}$ Mpc$^{-1}$.

2. The data

The 40 spiral galaxies considered for this study are drawn from a larger sample selected in the Pisces--Persesus supercluster region, for which $H$ band images are available (see Moriondo et al. 1998, 1999 for a thorough description of the original sample). This subset in particular contains the galaxies for which a RC is also available both from the literature or the private database of RG and MH, and includes morphological types ranging from Sa to Scd. In most cases, the RC’s are derived from optical emission lines measurements and are confined within two or three disk scale lengths. For a few galaxies radio aperture--synthesis RC’s (21 cm HI line) are also available, extending well beyond the optical radius. All the RC’s were rescaled to our adopted values of distance and inclination. For all the galaxies (except UGC 2885) 21 cm line velocity widths are also available from the database of RG and MH. We will use these values later on to derive the $H$ band TF relation for the sample. Table 1 contains the from the compilations by Corradi & Capaccioli (1991) and Prugniel et al. (1998). We note that this sample is not appropriate to obtain an absolute calibration of distances. It is however well suited to compare two different scaling relations and their relative accuracy as distance indicators.

3. The fits to the brightness distributions

The photometric data reduction and analysis are described in detail in Moriondo et al. (1998a, b). Briefly, each galaxy image is fitted with a model consisting of an exponential disk and a bulge, whose shape is described by a generalized exponential (Sérsic 1968). Both brightness distributions are assumed to be elliptical in the plane of the sky, and with a common centre and major axis. The parameters of the fit are the two scalelengths, surface brightnesses and apparent ellipticities (one for each component). The results of these decompositions were used in Moriondo et al. (1998a) to evaluate the effect of internal extinction on the $H$-band structural parameters and derive the corrections to the face-on aspect. The corrected values for scalelengths, surface brightnesses and total luminosities will be used in the following analysis. In most cases an exponential bulge yields a satisfactory fit to the data. For two galaxies in the subsample considered here (namely UGC 26 and UGC 820), a value $n = 2$ of the “shape” parameter in the exponent of the bulge brightness distribution produces better results. In two cases (UGC 673 and UGC 975) the disk alone is sufficient to fit the galaxy, i.e. no trace of a bulge is found in the brightness distribution. Table 2 contains the photometric parameters of the sample galaxies, corrected to the face-on aspect and for the redshift; the $H$--band total luminosity, in column 8, will be introduced in Sect. 5. The resulting decompositions are plotted in the top panels of Fig. 1, together with the surface brightness profiles averaged along elliptical contours (from Moriondo et al. 1999), and the brightness profiles along the major axis. In the case of UGC 673 and UGC 12666, the discrepancy between these two profiles is due to the ellipse--fitting routine, which in both cases has underestimated the galaxy apparent ellipticity in the regions of lower signal–to–noise ratio. Our fits, however, are in good agreement with the respective brightness distributions, so that the estimated parameters are reliable for these galaxies as well.

4. The fits to the rotation curves

To estimate the contribution of bulge and disk to a given RC we use the information from the photometric data to predict the shape of the RC’s of the two components, and derive their $M/L$ ratios from a best fit to the observed velocity profile. The accuracy of this technique, which has been used for a long time by many authors (van Albada...
Table 1. The galaxy sample

| Names         | R.A. (J2000) | Dec. | RH Type | $m_B$ | P.A. | $D$ (Mpc) | RC code |
|--------------|--------------|------|---------|-------|------|-----------|---------|
| UGC 00014    | 00 03 35.0   | 23 12 03 | Sc      | 13.8  | 41   | 92        | 1,2     |
| UGC 00026    | 00 04 24.5   | 31 28 19 | SB(s)b  | 14.2  | 99   | 61        | 3       |
| UGC 00089    | 00 09 53.4   | 25 55 25 | SB(s)a  | 12.8  | 171  | 56        | 4       |
| UGC 00673    | 01 06 09.7   | 31 24 24 | SAc?    | 15.7  | 45   | 79        | 1       |
| UGC 00725    | 01 10 11.0   | 43 06 35 | SBcd?   | 14.4  | 47   | 63        | 5       |
| UGC 00732    | 01 10 44.4   | 33 33 28 | SA(r)d  | 14.6  | 81   | 68        | 1       |
| UGC 00820    | 01 16 14.8   | 31 02 01 | SBab    | 13.6  | 35   | 62        | 6       |
| UGC 00927    | 01 23 11.5   | 33 31 46 | Sbc     | 14.1  | 38   | 76        | 1,7     |
| UGC 00940    | 01 23 37.9   | 34 34 11 | SA(s)c  | 15.1  | 68   | 89        | 7       |
| UGC 00975    | 01 25 15.6   | 34 21 34 | S       | 15.0  | 123  | 61        | 7       |
| UGC 01013    | 01 26 21.6   | 34 42 14 | SB(r)b  | 13.2  | 72   | 65        | 7       |
| UGC 01033    | 01 27 34.9   | 31 33 16 | Scd:    | 14.1  | 132  | 50        | 7       |
| UGC 01094    | 01 31 57.7   | 33 28 33 | SB?     | 14.1  | 60   | 54        | 7       |
| UGC 01238    | 01 46 22.6   | 36 27 39 | Sb      | 13.7  | 30   | 56        | 7,8     |
| UGC 01302    | 01 50 44.1   | 35 17 04 | (R')SAB(rs)b | 13.3 | 141  | 52        | 7,8     |
| UGC 01350    | 01 52 57.5   | 36 30 47 | SB(r)b  | 14.2  | 44   | 67        | 7       |
| UGC 01437    | 01 57 42.4   | 35 54 57 | SAB(rs)bc | 13.0 | 131  | 62        | 7,8,9,10 |
| UGC 01633    | 02 08 44.4   | 38 46 36 | SABc:   | 13.2  | 114  | 53        | 9,11    |
| UGC 01835    | 02 22 41.3   | 28 15 28 | Sc      | 13.7  | 5    | 65        | 1       |
| UGC 01935    | 02 28 14.5   | 31 18 42 | Sbc     | 14.5  | 82   | 64        | 1,12    |
| UGC 01937    | 02 28 10.9   | 19 35 59 | Scd:    | 13.6  | 153  | 52        | 13      |
| UGC 02134    | 02 38 51.8   | 27 50 50 | Sb      | 14.2  | 100  | 58        | 1       |
| UGC 02142    | 02 39 12.2   | 10 50 50 | (R')SAB(r)ab | 13.1 | 158  | 44        | 14      |
| UGC 02185    | 02 43 11.4   | 40 25 34 | Scd:    | 13.5  | 141  | 55        | 1       |
| UGC 02223    | 02 45 14.4   | 35 11 21 | Scd:    | 14.8  | 46   | 63        | 1       |
| UGC 02241    | 02 46 25.3   | 03 36 26 | SA(s)bc: | 13.1 | 2    | 88        | 15      |
| UGC 02617    | 03 16 00.7   | 40 53 08 | SAB(s)d | 13.8  | 10   | 59        | 7       |
| UGC 02655    | 03 18 45.3   | 43 14 20 | SAB(s)d | 13.5  | 80   | 7         |
| UGC 02885    | 03 53 02.4   | 35 35 22 | SA(rs)c | 13.5  | 45   | 76        | 10,16   |
| UGC 11973    | 22 16 50.4   | 41 30 13 | SAB(s)bc | 12.9 | 42   | 52        | 17      |
| UGC 12173    | 22 43 52.0   | 38 22 37 | SAB(rs)c | 13.5 | 101  | 39        | 1,7     |
| UGC 12230    | 22 53 21.2   | 32 07 44 | Sbc     | 13.9  | 160  | 81        | 1       |
| UGC 12378    | 23 07 32.5   | 22 59 50 | Sd      | 14.0  | 164  | 78        | 1       |
| UGC 12486    | 23 18 16.2   | 06 35 09 | SBbc    | 13.9  | 167  | 61        | 1,2,8,18 |
| UGC 12539    | 23 21 26.7   | 08 13 05 | SA(r)b: | 13.9  | 77   | 45        | 18      |
| UGC 12598    | 23 26 39.9   | 25 04 50 | Sc:     | 13.4  | 88   | 42        | 10,19   |
| UGC 12618    | 23 28 46.8   | 30 30 41 | SB0     | 13.5  | 64   | 20        |
| UGC 12666    | 23 33 41.0   | 32 23 02 | Scd:    | 14.4  | 124  | 62        | 1       |
| UGC 12667    | 23 33 49.5   | 30 03 37 | Scd:    | 13.5  | 127  | 46        | 1       |
| UGC 12780    | 23 47 04.7   | 29 29 01 | SAB(rs)bc | 12.8 | 71   | 64        | 21      |

Notes to Table 1.
Col. 5,6: from the Third Reference Catalogue of Bright Galaxies (RC3), de Vaucouleurs et al. 1991. Col. 7: from Moriondo et al. 1999. Col. 9: references for the rotation curves. 1: Courteau 1992; 2: Mathewson et al. 1992; 3: Szomoru et al. 1994; 4: Afanas’ev 1988a; 5: Van Moorsel 1983; 6: Oosterloo & Shostak 1993; 7: Vogt 1995; 8: Amram et al. 1994; 9: Broeils & Van Woerden 1994; 10: Rubin et al. 1980; 11: Márquez & Moles 1996; 12: Amram et al. 1992; 13: Blackman 1977; 14: Rubin et al. 1985; 15: Rubin et al. 1982; 16: Roelfsema & Allen 1985; 17: Afanas’ev 1988b; 18: Rubin et al. 1988; 19: Rhee & Van Albada 1996; 20: Jore 1997; 21: Marcelin et al. 1987.

dedge on the contribution of the dark component to the overall RC. This becomes certainly important at or beyond two disk scalelengths; low-
Fig. 1. Top panels: radial surface brightness profiles of the sample galaxies, in a magnitude scale. For each plot, the triangles represent the profile obtained by averaging the intensity over elliptical profiles (see Moriondo et al. 1999); the dotted line is a cut along the major axis of the galaxy; also shown are the best fit to the data (solid line) and the contributions from bulge (dot–dash line) and disk (dashed line). Bottom panels: the observed RC’s (triangles) with the best fit to the data (solid line). Again, the dot–dash and dashed lines represent the contributions from bulge and disk respectively. The contribution from the dark halo is shown as a dotted line.

Fig. 1. Continued

and Rix (1999) and Bottema (1993, 1997), for instance, estimate the disk contribution to be about 60% of the overall rotation at 2.2 scalelengths, whereas different authors (e.g. Verheijen & Tully 1998, Dubinski et al. 1999, Gerhard 1999, Bosma 1998) support a “maximum disk” scenario in which such contribution is about 85%, at least for bright galaxies. The shape of the dark matter distribution is rather uncertain as well: even the reliability of the distributions derived from numerical simulations of structure formation (e.g. Navarro et al. 1996) is weakened by their apparent discrepancy with the observed RC’s of low surface brightness galaxies. Since in this paper we are mainly interested in the properties of bulges and disks, the choice of the dark halo distribution is not likely to be important, at least as long as the visible matter dominates the mass distribution in the inner galaxy regions.

To have an idea of how the fit to the RC is influenced by the inclusion in the model galaxy of a dark component, we perform two different fits for each RC: one using only bulge and disk, and one including also the contribution from a dark halo. The expressions for the rotational velocity of an exponential disk and a generic ellipsoidal bulge are reported in Moriondo et al. (1998c), as well as two possible dark halo distributions, namely a constant density sphere and a pseudo–isothermal one (Kent, 1986). The first halo distribution yields a linearly rising RC, and is an approximation of the latter as $R$ tends to zero; the rotation velocity associated to the pseudo–isothermal sphere, on the other hand, tends to a constant value as $R$ goes to infinity. This last distribution has been considered only for the 4 galaxies whose RC is well sampled in the outer, flat part; this is also true when the dark matter distribution is well constrained by a very extended RC. In other words, the solutions we obtain are usually not very different from the “maximum disk” ones, implying that, in most cases, the visible part of the galaxy provides a good match to the observed RC; we will therefore assume that the “maximum disk” hypothesis is basically correct for our galaxies. An alternative scenario, however, will also be considered in Sect. 8. In a few cases the available RC is not extended enough to constrain even a constant density halo, and in these cases we use the results from the “bulge + disk” fits. We consider these values reliable, since in general the inclusion of the dark halo in the fits does not produce major changes in the estimated mass and $M/L$ of the visible components.

We also note that, in a few cases, at 2.2 $R_d$’s the contribution to the overall rotation from the bulge is still significant, so that the disk contribution is well below the measured circular velocity. In these cases neglecting the presence of the bulge would certainly lead to overestimate the disk mass and $M/L$.

Table 3 contains the parameters derived from the RC fits. Also included in the table are the values of the velocity width $W$ (corrected for instrumental smoothing, redshift, turbulence, and inclination), and of the velocity at 2.2 $R_d$, $V_2$ (corrected for redshift and inclination); both quantities will be introduced in the next section. In Fig. 1 (bottom panels) we show the best fits to the RC’s for all the galaxies in our sample.

In 17 cases out of 40, the observed RC has either no data-points in the innermost region (3 cases), or shows no evidence of contribution by the bulge. For these galaxies the bulge mass and $M/L$ are either unconstrained or likely to be underestimated. Most of the 14 galaxies, for which the disk contribution alone is sufficient to match the inner RC, are characterized by the smallest bulge-to-
Table 2. The photometric parameters

| Name      | $\mu_e$ (mag) | $R_e$ (kpc) | $e_b$   | $\mu(0)$ | $R_d$ (kpc) | $i$ (deg) | $M_H$ |
|-----------|---------------|-------------|---------|-----------|-------------|-----------|-------|
| UGC 00014 | 16.45         | 0.66        | 0.27    | 17.76     | 4.08        | 44.0      | -24.03|
| UGC 00026 | 17.93         | 0.94        | 0.16    | 19.51     | 5.69        | 55.9      | -23.14|
| UGC 00089 | 14.99         | 0.75        | 0.31    | 16.72     | 2.79        | 56.0      | -24.63|
| UGC 00673 | ...           | ...         | ...     | ...       | 18.10       | ...       | ...   |
| UGC 00725 | 18.55         | 0.35        | 0.01    | 18.20     | 3.40        | 76.9      | -23.00|
| UGC 00732 | 17.91         | 0.40        | 0.41    | 17.84     | 2.85        | 55.2      | -23.02|
| UGC 00820 | 16.00         | 0.81        | 0.22    | 16.82     | 2.85        | 67.0      | -24.50|
| UGC 00927 | 16.92         | 0.29        | 0.12    | 18.03     | 3.83        | 54.8      | -23.44|
| UGC 00940 | 19.14         | 0.68        | 0.15    | 18.86     | 4.16        | 49.2      | -22.86|
| UGC 00975 | ...           | ...         | ...     | ...       | 17.94       | ...       | ...   |
| UGC 01013 | 15.84         | 1.14        | 0.43    | 17.74     | 4.74        | 61.4      | -24.10|
| UGC 01033 | 17.56         | 1.15        | 0.75    | 18.53     | 2.87        | 81.3      | -22.82|
| UGC 01094 | 17.03         | 0.66        | 0.23    | 17.50     | 3.40        | 74.3      | -24.21|
| UGC 01238 | 16.53         | 0.85        | 0.14    | 18.08     | 3.02        | 42.3      | -23.38|
| UGC 01302 | 15.19         | 0.32        | 0.29    | 17.48     | 2.41        | 63.4      | -23.39|
| UGC 01350 | 17.35         | 0.94        | 0.35    | 18.34     | 6.15        | 51.1      | -24.25|
| UGC 01437 | 15.92         | 0.54        | 0.28    | 16.39     | 2.64        | 45.1      | -24.37|
| UGC 01633 | 16.26         | 0.47        | 0.42    | 16.63     | 2.76        | 61.6      | -24.22|
| UGC 01835 | 17.19         | 0.75        | 0.06    | 17.80     | 4.32        | 49.8      | -23.95|
| UGC 01935 | 14.97         | 0.50        | 0.43    | 17.18     | 4.33        | 72.3      | -24.88|
| UGC 01937 | 16.54         | 0.58        | 0.32    | 16.97     | 3.13        | 52.3      | -24.20|
| UGC 02134 | 17.51         | 0.95        | 0.15    | 18.71     | 4.15        | 66.4      | -23.89|
| UGC 02142 | 15.57         | 1.01        | 0.42    | 17.79     | 4.64        | 61.6      | -24.58|
| UGC 02185 | 17.17         | 0.22        | 0.16    | 17.81     | 3.64        | 74.8      | -23.56|
| UGC 02223 | 19.67         | 0.40        | 0.00    | 18.26     | 2.76        | 74.3      | -22.51|
| UGC 02241 | 17.75         | 1.93        | 0.20    | 18.24     | 4.20        | 50.7      | -23.93|
| UGC 02617 | 17.69         | 0.52        | 0.38    | 18.20     | 3.16        | 60.9      | -22.88|
| UGC 02655 | 18.65         | 1.93        | 0.15    | 18.97     | 2.66        | 62.6      | -23.64|
| UGC 02885 | 15.80         | 0.69        | 0.00    | 17.96     | 9.42        | 67.0      | -25.58|
| UGC 11973 | 16.90         | 0.35        | 0.27    | 16.84     | 2.61        | 72.4      | -24.57|
| UGC 12173 | 17.36         | 0.38        | 0.13    | 17.80     | 4.59        | 49.4      | -24.02|
| UGC 12230 | 17.34         | 0.49        | 0.13    | 17.00     | 3.10        | 57.9      | -24.01|
| UGC 12378 | 17.14         | 0.42        | 0.19    | 17.51     | 3.40        | 54.9      | -23.77|
| UGC 12486 | 15.74         | 0.66        | 0.00    | 17.92     | 4.04        | 56.8      | -24.12|
| UGC 12539 | 16.71         | 0.32        | 0.23    | 17.10     | 2.12        | 64.7      | -23.17|
| UGC 12598 | 16.24         | 0.23        | 0.16    | 16.22     | 1.43        | 58.6      | -23.18|
| UGC 12618 | 15.49         | 0.65        | 0.03    | 16.81     | 2.01        | 22.6      | -23.83|
| UGC 12666 | 19.32         | 1.46        | 0.33    | 19.60     | 6.97        | 74.3      | -23.14|
| UGC 12677 | 17.73         | 0.28        | 0.38    | 17.94     | 2.84        | 53.1      | -22.82|
| UGC 12780 | 16.14         | 0.61        | 0.06    | 17.23     | 4.75        | 39.8      | -24.81|

Notes to Table 2.
Col 2: bulge effective surface brightness, in mag arcsec$^{-2}$. Col. 3: bulge effective radius. Col. 4: bulge ellipticity. Col. 5: disk central surface brightness in mag arcsec$^{-2}$. Col 6: disk scalelength. Col. 7: disk inclination. Col. 8: Total absolute magnitude.

ing, therefore, that in these cases the bulge contribution to the overall RC cannot be adequately resolved. A direct comparison between the $M/L$ of disks and bulges seems to confirm these statements. In Fig. 3 mass versus luminosity is plotted for the disks, and for the bulges with $M_b > 10^5 M_\odot$. These are the 23 cases for which we obtain a reliable fit to the RC for both components, and the two delimited by $M/L = 0.25$ and $M/L = 2.5$, in solar units. The remaining “low mass” bulges are placed well below the sequence, out of the plot window, suggesting that their mass is largely underestimated. In the following analysis, therefore, we will consider only the bulges plotted in Fig. 3.
Table 3. The dynamical parameters

| Name       | $M_b$ (10$^9$ M$_\odot$) | $(M/L)_b$ | $M_d$ (10$^9$ M$_\odot$) | $(M/L)_d$ | $W$ (km s$^{-1}$) | $v_2$ (km s$^{-1}$) |
|------------|-------------------------|-----------|------------------------|-----------|-----------------|-------------------|
| UGC 00014  | 12.2                     | 0.95      | 97.5                   | 1.25      | 456.7           | 215.0             |
| UGC 00026  | ...                      | ...       | 22.5                   | 0.74      | 271.6           | 90.0              |
| UGC 00089  | 21.7                     | 0.34      | 29.2                   | 0.31      | 445.2           | 180.0             |
| UGC 00673  | ...                      | ...       | 8.9                    | 0.70      | 299.2           | 120.0             |
| UGC 00725  | ...                      | ...       | 24.5                   | 0.68      | 293.1           | 160.0             |
| UGC 00732  | ...                      | ...       | 17.4                   | 0.49      | 289.7           | 120.0             |
| UGC 00820  | ...                      | ...       | 55.1                   | 0.61      | 462.7           | 240.0             |
| UGC 00927  | ...                      | ...       | 34.7                   | 0.64      | 314.3           | 150.0             |
| UGC 00940  | ...                      | ...       | 65.7                   | 2.22      | 328.8           | 160.0             |
| UGC 00975  | ...                      | ...       | 13.1                   | 1.01      | 275.0           | 128.0             |
| UGC 01013  | 181.1                    | 2.64      | 81.1                   | 0.75      | 550.9           | 300.0             |
| UGC 01033  | 10.2                     | 0.72      | 12.7                   | 0.67      | 323.1           | 160.0             |
| UGC 01094  | 3.9                      | 0.51      | 49.2                   | 0.71      | 435.2           | 212.0             |
| UGC 01238  | 8.9                      | 0.70      | 299.2                  | 0.91      | 397.9           | 180.0             |
| UGC 01302  | 21.7                     | 0.34      | 29.2                   | 0.65      | 353.9           | 190.0             |
| UGC 01350  | ...                      | ...       | 169.2                  | 1.63      | 731.3           | 240.0             |
| UGC 01437  | 6.6                      | 0.46      | 49.6                   | 0.43      | 420.1           | 205.0             |
| UGC 01633  | 4.5                      | 0.58      | 56.9                   | 0.56      | 479.4           | 240.0             |
| UGC 01835  | 10.2                     | 1.20      | 65.4                   | 0.77      | 423.2           | 207.0             |
| UGC 01935  | 1.4                      | 0.05      | 46.8                   | 0.31      | 447.0           | 200.0             |
| UGC 01937  | ...                      | ...       | 56.5                   | 0.60      | 437.8           | 200.0             |
| UGC 02134  | 15.5                     | 1.56      | 34.8                   | 0.45      | 335.6           | 160.0             |
| UGC 02142  | 65.1                     | 0.95      | 109.2                  | 1.12      | 520.1           | 250.0             |
| UGC 02185  | ...                      | ...       | 37.6                   | 0.63      | 437.1           | 200.0             |
| UGC 02223  | ...                      | ...       | 7.2                    | 0.32      | 244.9           | 125.0             |
| UGC 02241  | 82.3                     | 2.46      | 44.6                   | 0.84      | 461.9           | 250.0             |
| UGC 02617  | ...                      | ...       | 22.4                   | 0.72      | 535.4           | 138.0             |
| UGC 02655  | 9.1                      | 0.62      | 30.1                   | 0.65      | 307.0           | 140.0             |
| UGC 02885  | 33.8                     | 2.12      | 185.7                  | 0.54      | ...             | 280.0             |
| UGC 11973  | ...                      | ...       | 104.1                  | 0.73      | 503.2           | 360.0             |
| UGC 12173  | 5.2                      | 2.80      | 104.2                  | 1.10      | 465.3           | 210.0             |
| UGC 12230  | ...                      | ...       | 83.1                   | 0.92      | 517.0           | 260.0             |
| UGC 12378  | 1.3                      | 0.47      | 52.3                   | 0.77      | 407.4           | 200.0             |
| UGC 12486  | 33.1                     | 1.32      | 61.9                   | 0.93      | 432.6           | 210.0             |
| UGC 12539  | 2.2                      | 0.92      | 21.5                   | 0.56      | 375.2           | 160.0             |
| UGC 12598  | ...                      | ...       | 18.8                   | 0.48      | 360.2           | 170.0             |
| UGC 12618  | 14.1                     | 0.47      | 36.2                   | 0.80      | 630.9           | 215.0             |
| UGC 12666  | 3.8                      | 0.84      | 47.0                   | 1.12      | 271.9           | 150.0             |
| UGC 12667  | ...                      | ...       | 21.5                   | 0.67      | 253.7           | 140.0             |
| UGC 12780  | 1.3                      | 0.09      | 161.0                  | 0.94      | 515.8           | 260.0             |

Notes to Table 3.
Cols. 2,4: masses in units of 10$^9$ M$_\odot$. Cols. 3,5: M/L’s in solar units.

5. The Tully Fisher relation for the sample

To derive an H-band TF relation for our galaxies the 21 cm line velocity widths from the RG and MH database (Table 3) have been corrected for instrumental smoothing, redshift, turbulence, and inclination of the galaxy to the line of sight, according to the prescriptions in Giovanelli brightness profiles extrapolated up to 8 disk scalelengths; a small correction to face-on aspect is applied, using the results obtained for the disks alone in Moriondo et al. (1998b). Figure 3 shows the plot we obtain, with the best fit to the data after the exclusion of the three discrepant points to the right. In the case of UGC 12618, our value for the inclination is probably underestimated, leading to an exceedingly large correction for $W$.
Fig. 2. Mass versus luminosity plotted for bulges and disks of our sample galaxies. Open circles represent the bulges, whereas filled triangles represent the disks. Only bulges with mass $>10^9 M_\odot$ are plotted. The slope of the two dashed line is of constant $M/L$. The two $M/L$ values plotted, 2.5 and 0.25, are in solar units ($H$ band).

Fig. 3. The $H$-band Tully-Fisher relation for our sample, with the best fit to the data after the exclusion of the three discrepant points on the right side. Different symbols correspond to different morphological types: filled circles for Sa-Sab, filled squares for Sb-Sbc, open squares for Sc-Scd, crosses for Sd and dm.

to the fit is not very significant anyway. In the case of UGC 1350 and UGC 2617, the observed $W$ is likely to be overestimated, maybe for a misidentification of the galaxy; we note that for these two objects an estimate of the rotation derived from the RC is, respectively, about 75% and 50% smaller than $W$.

The errors on both axes are of comparable magnitude, therefore the weight for each data point is the RMS of the two contributions. Since the relation we fit is $y = ax + b$, the $i$-th residual is weighted by

$$w(i) = \frac{1}{\sqrt{\epsilon_y^2(i) + a^2\epsilon_x^2(i)}}^{-1},$$

where the $\epsilon$’s are the estimated errors. The slope and zero offset, with respect to the average $\log W$, are respectively $-7.7 \pm 1.0$ and $-23.67 \pm 0.08$.

6. Fundamental Planes

We now fit separately to bulges and disks a relation

$$\log R = a \log V + b \log I + c$$

involving a scalelength, a velocity, and a surface brightness, analogous to the FP of elliptical galaxies. The designated parameters for the bulges are the effective radius $R_e$, the surface brightness at $R_e$ ($I_e$), and a velocity defined as

$$V_b = \sqrt{\frac{M_b}{R_e}}$$

where $M_b$ is the bulge mass, in units of $10^9 M_\odot$. Since for all have the same shape – this velocity scales as the rotation velocity, measured at 2.2 bulge scalelengths $R_b$. Also, $R_e$ and $I_e$ are related by constant factors respectively to $R_b$ and the central surface brightness $I(0)$ (the two parameters usually adopted for the disks): $R_e = 1.67 R_b$, and $I_e = 0.19 I(0)$. For the disks we choose the exponential scalelength $R_d$, the central surface brightness $I(0)$, and a velocity $V_d$ defined via a relation analogous to Eq. (4), with the disk mass and the disk scalelength. Again, this velocity differs from the value at 2.2 $R_d$ by the same factor for all the exponential distributions. Following CY95, we also consider a relation involving $R_d$, $I(0)$, and the total galaxy rotation velocity at 2.2 $R_d$, derived directly from the RC, which we will indicate as $V_2$.

It turns out that the three parameters to be fitted have comparable uncertainties, and each point needs to be weighted by a combination of them. In the case of the structural parameters ($R$, $I$), besides the formal error from the fit to the brightness distributions, a major contribution is added from the errors in the corrections to face-on aspect, that is from the uncertainty in the amount of internal extinction. These are evaluated according to the results in Moriondo et al. (1998). The uncertainty on the velocity depends in principle on the errors associated both to the RC measurement and to the scale length. However we expect this latter contribution to be less important, especially for the disks, whose scalelength is always the best determined parameter in the surface brightness decompositions. Therefore we assume the uncertainty on the velocities to be well represented by the formal error derived from the fitting routine. The errors on all other quantities are derived from these values: for example, the error on the disk mass is obtained combining the uncertainties on the velocity and the scale length, since $M \sim V^2 R$.

The fit to the disk parameters yields

$$\log R_d = (1.31 \pm 0.19) (\log V_d - < \log V_d >) + (-0.62 \pm 0.09) (\log I(0) - < \log I(0) >) + 1.29 \pm 0.07 \ ,$$

where “$<$” designates the average over the sample. If $V_2$ is chosen, instead of the value defined in terms of the disk mass and scalelength, we obtain

$$\log R_d = (1.47 \pm 0.16) (\log V_2 - < \log V_2 >) + (-0.61 \pm 0.07) (\log I(0) - < \log I(0) >) + 1.39 \pm 0.06 \ .$$

We note that these coefficients are close to the values implied by the TF relation derived in Sect. 3 in fact, from $L \sim W^{3.1}$, we derive $R \sim W^{1.5} I^{-0.5}$. Therefore, the TF relation is a nearly edge-on projection of the FP. Also, these values are not inconsistent with the constraint imposed by the RC.
The various sets of coefficients can also be compared to the ones which define the FP of elliptical galaxies, evaluated using the central velocity dispersion as the kinematical parameter. This work improves the approach by characterizing separately bulges and disks from the photometric point of view; in addition, we are able to determine the bulge mass independently of its kinematical status (i.e., if it’s more or less supported by rotation), and obtain an independent estimate of the coefficients of the bulge FP.

Figure 6 shows our data in the $H$–band $k$–space, with bulges denoted as open circles, and disks as triangles. We have defined the three coordinates as $k_1 = \log(M)$, $k_2 = \log(M/L \cdot I_e^3)$, and $k_3 = \log(M/L)$, where $M$ is the total mass in units of $M_\odot$, $M/L$ is the stellar mass–to–light ratio in solar units, and $I_e$ is the effective surface brightness in $L_\odot/pc^2$. These definitions, besides being applied to a different passband, are slightly different from the ones introduced by Bender et al. (1992). We can calculate the transformations between the two sets of coordinates from the relations reported in the Appendix A to BBFN, and assuming that all our bulges and disks are adequately described by exponentials. Using a typical $B − H = 3.5$ for both components, we find

$$\begin{align*}
k_1^B &= \frac{1}{\sqrt{2}} (k_1 - 5.97) \\
k_2^B &= \frac{1}{\sqrt{6}} (k_2 + 0.58) \\
k_3^B &= \frac{1}{\sqrt{6}} (k_3 + 1.37)
\end{align*}$$

(8)

where $k_1^B$, $k_2^B$, and $k_3^B$ are the $B$–band BBFN parameters. The dotted line in the upper right corner of the $k_1$ vs. $k_2$ plot corresponds, in our set of coordinates, to the boundary of the so–called Zone of Exclusion (ZOE), defined in the $B$ band by $k_1^B + k_2^B > 8$: it is consistent with our data, in the sense that most bulges and all the disks are placed to its left side. The BBFN database for the bulges is here extended to lower masses, with several data–points falling in the typical range of dwarf ellipticals ($M < 10^{10}M_\odot$); the two classes of objects appear however separated, with the bulges shifted towards higher values of $k_2$, and therefore higher concentrations (note that, for $k_3 < 1$)
Fig. 7. Bulges (open circles) and disks (triangles) in the $k-$space defined by Bender et al. (1992). In the top panel the slope of the FP for elliptical galaxies is plotted for comparison. In the $k_1$ versus $k_2$ panel the dotted line represents the Zone of Exclusion, as defined by BBFN.

For what concerns spiral galaxies, BBFN find that their average distance from the ZOE increases steadily with morphological type, from Sa’s to Irregulars; the data points of our disks, however, are all placed in about the same region of the $k_1-k_2$ plane, quite distant from the ZOE, and roughly coincident with the locus occupied by Scd’s galaxies in the BBFN’s plots. Most likely, this difference arises from the separation of the two structural components, which has allowed us to plot the $k$ parameters of the disks alone: if the values for the whole galaxies are considered, one would expect the systems with higher $B/D$ (namely, the early–type spirals) to lie closer to the ZOE, due to the contamination of the bulge. The BBFN sequence, therefore, would be mainly driven by the average $B/D$, which in turn is roughly correlated with morphological type. When considered separately, on the other hand, disks and bulges are located in two distinct, contiguous regions of the $k-$space, as it is also evident from the $k_3-k_3$ projection, with the disks shifted towards higher masses and lower concentrations. A different ZOE could in principle be defined for the disks, with about the same slope but shifted by about two decades towards lower $k_2$ values.

In the top panel of Fig. 7, we have plotted the slope of the $B-$band FP for the Virgo cluster, scaled to the centoid of the bulges (dashed line) and of the disks (solid line). It appears to be consistent with our data, as suggested by the similarity of our coefficients in Eqs. (6) and (7) to the ones reported by Bender et al. (1992). Also, using Eqs. (6) and the definition in BBFN, we can estimate the quantity $\delta_{3:1}$ for bulges and disks, representing their average vertical distance from the ellipticals’ FP in the $k_1^B-k_3^B$ projection. In the case of the bulges, we find $\delta_{3:1}=0.03$ dex, in fair agreement with the BBFN estimate (-0.03); for the disks we find a shift of +0.19 dex, which is about the value found by BBFN for spirals from type Sa to Sc.

7. The disk FP as a distance indicator

In order to assess the goodness of Eqs. (6) and (7) as tools to measure galaxy distances, we compare the scatter of the data points, with respect to the best fit, to the scatter associated to the TF relation. The dispersion is defined as

$$\Delta_i = w_i \| r - M/L \|$$

where $\Delta_i$ is the residual on the i-th data point and $w_i$ the associated weight, defined by Eq. (8). We find a dispersion of 0.38 mag for the TF relation, implying an uncertainty of 19% on the distance of a single galaxy. We note that the galaxy distances used in this context have been estimated purely from redshifts. The peculiar velocity field thus adds scatter to the corresponding TF relation in a measure which we estimate to be in the range of 0.15 to 0.20 mag, at the typical distance of these objects. Had peculiar velocity–corrected distances been used, the TF scatter would have been so that distance estimates would have uncertainties of about 16%, rather then 19%.

In the case of the FP, we find a dispersion of 0.11 in log $r$ if we use velocities derived from the best fits (Eq. (6)), and of 0.09 if the velocities are the actual rotation velocities (Eq. (7)). The associated uncertainties in the distance are respectively about 29% and 23%. Even if these two values are less than 1/2 of the dispersion quoted by Giovanelli for the relation proposed by Cy95 and a sample of 153 spiral galaxies (0.25 in log $r$, not based on a detailed disk–bulge decomposition analysis as we use here), they are still larger than the uncertainty yielded by the TF relation for our sample. Therefore, according to our data, the disk FP is not as accurate, as a distance indicator, as the TF relation, even if it allows for one more free parameter in the relation. This result could be imputed to the scatter added to the relation by the uncertainties introduced in the data analysis process (in particular, the decomposition of the surface brightness distribution and the fit to the RC). On the other hand, we find that a modified Tully-Fisher relation, in which the velocity width is replaced by $V_2$, is characterized as well by a larger dispersion of 0.45 mag. This value is equivalent to the dispersion of 0.09 in log $r$ associated to Eq. (6). In a similar way, if the total luminosity is replaced by the luminosity within 2.2 $R_d$’s, we find a very large dispersion of 0.64 mag. Since these alternative parameters are not strictly derived from the surface brightness decompositions or by the fit to the RC’s, as it is the case for the FP ones, we argue that using parameters associated with the inner part of the galaxy (rather than global quantities), is in itself a major source of scatter in the scaling relation considered. Thus, the fine tuning between photometric and kinematic parameters that yield the TF relation would be more effective because of their global character. About the much reduced dispersion with respect to the Giovanelli data, we attribute this difference to the use of a more refined data-analysis technique for our sample.

8. The relation between mass and luminosity

Eqs. (6)–(7) show that for both disks and bulges a systematic variation of $M/L$ exists, if we assume that we
tribution to the RC. In particular we can rewrite Eqs. (8) and (9) as
\begin{align}
L_d & \sim \frac{M_d^{1.0 \pm 0.2}}{R_d^{0.7 \pm 0.4}}, \\
\text{and} \\
L_b & \sim \frac{M_b^{0.8 \pm 0.2}}{R_e^{0.5 \pm 0.3}}.
\end{align}

Whereas for elliptical galaxies the mass–light plane shows an edge-on view of the FP, this is not the case for disks and bulges, and a residual dependence on the scalelength is left; this dependence is such that, if a given mass settles into a larger size, the corresponding \(M/L\) ratio is larger. Actually, this result is already implicit in the work by CY95: a good match to equation 1 with the results by Bo(1993, 1997) and by Courteau & Rix (1999) support a scenario of this kind, with the disk contributing, on average, about 60% of the rotation at 2.2 \(R_d\) s. Assuming that this rule holds for our sample as well, then, Eq. (12) predicts that the ratio \(V_d/V_2\) should vary throughout the sample between about 0.45 and 0.75, in a well defined way according to the size and surface brightness of each disk. Neglecting the presence of the bulge, and assuming an infinitely thin disk, the corresponding ratio of dark to visible mass within \(R_2\) can be expressed as
\[M_h/M_d \sim 0.8 \left( \frac{V_2}{V_d} \right)^2 - 1.\]

This quantity changes by more than a factor of 8 in our sample, from 0.4 to 3.3, whereas in the “maximum disk” hypothesis it stays roughly constant: in principle, the predictions of a reliable model for galaxy formation could help to distinguish between two such different behaviours.

Of course, any intermediate scenario between the two extremes discussed here (“maximum disk” solutions and constant stellar \(M/L\) could be considered as well. From the observational point of view, again, more detailed spectrophotometric data might better constrain possible variations in the average stellar population of different galaxies, and help to distinguish between the different possibilities.

9. Summary

Using near–infrared images and rotation curves of a sample of 40 spiral galaxies, we have determined the scaling relations, between structural and kinematic parameters of bulges and disks, analogous to the Fundamental Plane of elliptical galaxies. The accuracy of the disk FP as a distance indicator, for this set of data and our photometric
decompositions, is comparable but slightly lower than the one attained by the Tully–Fisher relation. This suggests that the fine tuning between dark and visible components at the basis of the various scaling relations is more effective for global parameters. Also, we deduce that (a) either the stellar mass-to-light ratio of the disk increases with $R_d$, or (b) the disk contribution to the observed RC decreases according to Eq. 12 for galaxies of large size. A similar behaviour is observed for the bulges.

Acknowledgements. We would like to thank the referee, A. Bosma, for his careful reading of the manuscript, C. Giovanardi and L. Hunt for insightful comments and suggestions, and Stephane Courteau for having provided his data in electronic format. This research was partially funded by ASI Grant ARS–98–116/22. Partial support during residency of G.M. at Cornell University was obtained via the NSF grant AST96–17069 to R. Giovanelli.

References

Afanas’ev V.L., Burenkov A.N., Zasov A.V., et al., 1988a, Astrofizika 28, 243
Afanas’ev V.L., Burenkov A.N., Zasov A.V., et al., 1988b, Astrofizika 29, 155
Amram P., Marcelin M., Bonnarel F., et al., 1992, A&A 263, 69
Amram P., Marcelin M., Balkowski C., et al., 1994, A&AS 103, 5
Bender R., Burstein D., Faber S.M., 1992, ApJ 399, 462
Bender R., Burstein D., Faber S.M., 1997, in the proceedings of “Galaxy Scaling Relations: Origins, Evolution and Applications”, da Costa & Renzini eds., 1997, Springer–Verlag, p. 95
Blackman C.P., 1977, MNRAS 178, 15
Bosma A., 1998, astro-ph/9812013
Bottema R., 1993, A&A 275, 16
Bottema R., 1997, A&A 328, 517
Broeils A.H., van Woerden H., 1994, A&AS 107, 129
Burstein D., Bender R., Faber S.M., et al., 1997, AJ 114, 1365 (BBFN)
Chiba M., Yoshii Y., 1995, ApJ 442, 82 (CY95)
Cioffi L., 1997, in the proceedings of “Galaxy Scaling Relations: Origins, Evolution and Applications”, da Costa & Renzini eds., 1997, Springer–Verlag, p. 38
Corradi R.I.M., Capaccioli M., 1991, A&AS 90, 121
Courteau S., 1991, Ph.D. Thesis
Courteau S., Rix H., 1999, ApJ 513, 561
Dalcanton, J.J., Spergel D.N., Summers, F.J., 1997, ApJ 482, 659
de Blok, W.J.G., McGaugh S.S, 1997, MNRAS 290, 533
de Vaucouleurs G., de Vaucouleurs A., Corwin Jr. H.G., et al., 1991, Third Reference Catalogue of Bright Galaxies (Springer-Verlag, New York)
Dubinski J., Mihos J.C., Hernquist L., 1999, astro-ph/9902217
Gavazzi G., 1993, ApJ 419, 469
Gavazzi G., 1997, in the proceedings of “Galaxy Scaling Relations: Origins, Evolution and Applications”, da Costa & Giovanelli R., 1997, in the proceedings of “Galaxy Scaling Relations: Origins, Evolution and Applications”, da Costa & Renzini eds., 1997, Springer–Verlag, p. 146
Giovanelli R., Haynes M.P., Herter T., et al., 1997, AJ 113, 53
Giovanelli R., Dale D., Haynes M.P., et al., 1998, AJ, submitted
Jore K., 1997, Ph.D. thesis (Cornell University)
Jørgensen I., Franx M., Kjærgaard P., 1996, MNRAS, 280, 167
Karachentsev I., 1989, AJ 97, 1566
Kent S.M., 1986, AJ 91, 1301
Marcelin M., Lecoarer E., Boulesteix J., et al., 1987, A&A 179, 101
Mármol I., Moles M., 1996, A&AS 115, 407
Martinbecau M., Carignan C., Roy J., 1994, AJ 107, 543
Mathewson D.S., Ford V.L., Buchhorn M., 1992, ApJS 81, 413
Moriondo G., Giovanardi C., Hunt L.K., 1998a, A&AS 130, 81
Moriondo G., Giovanelli R., Haynes M.P., 1998b, A&A 338, 795
Moriondo G., Giovanardi C., Hunt L.K., 1998c, A&A 339, 409
Moriondo G., Baffa C., Casertano S., et al., 1999, A&AS, in press
Navarro J.F., Frenk C.S., White S.D.M., 1996, AJ 462, 563
Navarro J.F., 1998, astro-ph/9807084
Oosterloo T., Shostak S., 1993, A&AS 99, 379
Pahre M.A., Djorgovski S.G., de Carvalho R.R, 1998a, AJ 116, 1591
Pahre M.A., de Carvalho R.R, Djorgovski S.G., 1998b, AJ 116, 1606
Peletier R.F., de Grijs R., 1998, MNRAS 300, L3
Persic M., Salucci P., Stel F., 1996, MNRAS 281, 27
Prugniel P., Zasov A., Busarello G., et al., 1998, A&AS 127, 117
Rhee M.H., van Albada T.S., 1996, A&AS 115, 407
Roelfsema P.R., Allen R.J., 1985, A&A 146, 213
Rubin V.C., Ford W.K., Thonnard N., 1980, ApJ 238, 471
Rubin V.C., Ford W.K., Thonnard N., 1982, ApJ 261, 439
Rubin V.C., Burstein D., Ford W.K., et al., 1985, ApJ 289, 81
Rubin V.C., Whitmore B.C., Ford W.K., 1988, ApJ 333, 522
Scodeggio M., 1997, Ph. D. thesis (Cornell University)
Sérsic J.L., 1968, Atlas de Galaxias Australes (Cordoba: Observatorio Astronomico)
Szomoru, A., Guhathakurta P., van Gorkom J.H. et al., 1994, AJ 108, 491
Tully, R.B., Fisher, J.R., 1977, A&A 54, 661
Tully R.B., Pierce M.J., Huang J., et al., 1998, AJ 115, 2264
van Albada T.S., Bahcall J.N., Begeman K., et al., 1985, ApJ 295, 305
van Moorsel G.A., 1983, A&AS 54, 19
Verheijen M., Tully B., 1998, astro-ph/9810297
Vogt N.P., 1995, Ph.D. thesis (Cornell University)
