University of Groningen

Edge-on disk galaxies

Grijs, Richard de

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
1997

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Grijs, R. D. (1997). *Edge-on disk galaxies: a structure analysis in the optical and near-infrared*. s.n.

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 23-05-2025

Chapter 6

The optical/near-infrared colour-magnitude relation in disk galaxies

Abstract. Dust-free colours and near-infrared absolute magnitudes greatly enhance the usefulness of the optical/near-infrared colour-absolute magnitude (CM) relation as a secondary distance indicator for disk galaxies. We show that by avoiding contamination by dust we are able to reduce the scatter in the CM relation significantly, compared to similar galaxy samples published previously. The CM relation can be used to determine distances in a statistical sense and large-scale structures for galaxies having absolute K-band magnitudes $M_K > -25.5$ and down to at least $M_K \approx -20$. Brighter galaxies exhibit a roughly constant intrinsic I–K colour.
We show that the accuracy of the optical/near-infrared CM relation for estimating relative distances can be comparable to that of the widely used Tully-Fisher relation (TFR); the intrinsic scatter in the absolute K-band magnitudes is ~ 0.5 mag.
Our results, supplemented with previously published observations, are consistent with a universal nature of the CM relation for disk galaxies.
High-resolution observations done with the *Hubble Space Telescope* can provide a powerful tool to extend the useful distance range and calibrate the relation.

1 Introduction

Baum (1959) and de Vaucouleurs (1961) first established, from optical observations, that early-type galaxies obey a tightly constrained colour – absolute magnitude (CM) relation. This correlation is usually attributed to metallicity changes, assuming that it is caused by the fact that the more luminous galaxies have greater binding energies and thus longer time scales for gas processing (e.g., Mathews & Baker, 1971; Faber, 1977; Arimoto & Yoshii, 1987).

Therefore, the CM relation provides an observational test for galaxy formation models (cf. Ellis et al., 1997, and references therein) and for galaxy synthesis models (e.g., Tinsley, 1978; Aaronson et al., 1978).

Because of the tightness of the correlation it is potentially useful as a (secondary) distance indicator, as was first suggested by Sandage (1972) for elliptical and S0 galaxies. In this Chapter we investigate whether the optical / near-infrared CM relation is also useful as a potential diagnostic to estimate distances to spiral galaxies, by using near-infrared absolute magnitudes and I–K colours that were determined in those regions of edge-on disk galaxies that are least affected by the effects of dust.

1.1 *Ellipticals versus spiral galaxies*

Although the CM relation for elliptical and lenticular galaxies is well-established, the situation for spiral galaxies is more ambiguous. Motivated by the close agreement between the CM relations for ellipticals and S0s, which show a clear bulge-disk geometry, Visvanathan & Griersmith (1977) extended the range of galaxy types to early-type spirals (S0/a to Sab). They found, within the errors, exactly the same optical CM relation for their early-type spirals in the Virgo cluster as had been found for E/S0 galaxies. However, the excess scatter is larger for early-type spirals than for E/S0s (Griersmith, 1980).

For later-type spirals Tully et al. (1982), using the hybrid $B_T - H_{-0.5}$ colour, found that early and late-type spiral galaxies occupy completely different places in the CM diagram, with the early-type galaxies lying on the blue side of the elliptical and lenticular galaxies. However, some of their S0 galaxies are redder than their bright elliptical galaxies, whereas Balcells & Peletier (1994) show that the colours of the stellar populations of bulges of early-type galaxies are always bluer than or have the same colour as those of ellipticals of the same luminosity. Therefore, these S0's likely suffer from a considerable amount of extinction, which seems to be in conflict with the very small scatter among S0 galaxies.

Moreover, they found a considerable gap between the loci of the S0 galaxies and the early-type spirals, which has not been confirmed by other work. Mobasher et al. (1986) showed, from optical and near-infrared observations, that although the E/S0 galaxies and the early-type spirals occupy separate branches in the CM diagram the bright ends of these branches coincide. In a subsequent paper (Peletier & de Grijs, 1997) we will confirm Mobasher et al.'s (1986) result for the spiral galaxies from this study and the Virgo ellipticals studied by Bower et al. (1992).

Tully et al. (1982) claimed that the difference between the loci of spiral and E/S0 galaxies in the CM diagram could be explained by significantly more ongoing star formation in late-type spirals. This star formation would affect the blue light in particular, and hence the B–H colour. Moreover, the fact that spirals are much bluer than lenticulars for the same absolute magnitude indicates that metallicity variations play only a secondary role here.

Apart from the distinction between spirals and E/S0s, Griersmith (1980) noticed that, although for early-type spirals the slopes of the CM relations derived for individual (early) galaxy types are the same within the errors compared to each other and compared to E/S0 galaxies, differences in zero point of the CM relations seem to follow a systematic trend along the Hubble sequence: colours become systematically bluer for later Hubble types.

1.2 Environmental effects

Visvanathan & Sandage (1977) found that the dispersions about the CM relation for early-type galaxies in eight nearby groups and clusters are nearly the same as for the Virgo cluster. The agreement is particularly remarkable in view of the fact that these eight groups and clusters are of different richness and cluster type. This, and their observation that the CM correlation also applies to galaxies in the general field, led them to the conclusion that the CM relation is not affected by the ambient medium of the galaxies (Visvanathan & Griersmith, 1977; Visvanathan & Sandage, 1977; Griersmith, 1980).

Griersmith (1980) studied the optical CM relation ($U-V$ and $B-V$ vs. M_V) for a sample of 119 early-type spirals, from which he concluded that also for early-type spirals the CM relation is independent of environment. If one assumes that in early-type spirals the colours refer primarily to the bulge component, which seems reasonable since in most early-type spirals the bulge is the dominant luminosity component, then this result suggests that the stellar population in the bulges of early-type spirals was determined by the initial collapse at the period of active star formation and not by environmental factors.

Recently, Ellis et al. (1997) established that the scatter about the UV-optical CM relation of early-type galaxies between 3 clusters of different richness at moderate redshift is smaller than the internal scatter within each cluster, which again indicates that environmental effects do not play a significant role.

1.3 A universal CM relation?

Provided that the CM relation is universally applicable it can be used as a (secondary) distance indicator. In this section we will discuss the existing evidence for a universal CM relation for E/S0 galaxies. In the remaining part of this Chapter, we will use our own optical and near-infrared observations of edge-on disk galaxies, supplemented with similar samples from the literature, to investigate the possible universality of the CM relation for later-type spiral galaxies.

Following the discovery of the CM effect for the early-type Virgo cluster members, many attempts have been made to unambiguously determine the universality of the relationship (e.g., Visvanathan & Sandage, 1977; Visvanathan & Griersmith, 1977; Griersmith, 1980; Aaronson et al., 1981; Bower et al., 1992a,b). In general, the optical CM relation for early-type galaxies was found to be universal and independent of environment, either by determination of the absolute magnitudes by redshift scaling or vice versa.

However, Faber (1977), Burstein (1977) and Larson et al. (1980) criticized the tests done to study the universality of the CM effect. They pointed out that there were non-negligible environmental effects playing a role in the observations obtained.

Aaronson et al. (1981) challenged the claims for universality of the CM relation even more seriously. They extended the colour baseline by adding near-infrared observations to their sample of Virgo and Coma cluster galaxies, from which they found a significant difference between relative Coma-Virgo distance moduli derived from the $U-V$ and $V-K$ colours.

To undertake an independent study of the universality of the CM effect, Bower et al. (1992a,b) obtained new observations of Virgo and Coma cluster galaxies. Contrary to Aaronson et al.'s (1981) result, Bower et al.'s (1992b) observations support a universal CM relation, also based on $U-V$ and $V-K$ measurements. They claim that to an accuracy of better than 0.04 mag, the $U-V$ and $V-K$ colours of galaxies in the Virgo and Coma clusters follow exactly the same CM relationship. Bower et al. (1992b) argued that part of the discrepancy between their and Aaronson et al.'s (1981) result could be explained by the inhomogeneous nature of the optical data used by Aaronson et al. (1981), as well as by the difficulties in their calibration of the faintest sample galaxies. The remainder of the discrepancy is likely due to small differences in the galaxy samples used and to artifacts caused by the numerical technique used by Aaronson et al. (1981).

1.4 Advantages of near-infrared observations

Although the change of colour with absolute magnitude is greatest in the ultraviolet, and decreases significantly towards redder wavelengths (Visvanathan & Sandage, 1977, and references therein), the CM effect again shows up in the optical/near-infrared regime, in the sense that $V-K$ is bluer for intrinsically fainter galaxies (e.g., Aaronson et al., 1981; Tully et al., 1982).

The usefulness of near-infrared observations of spiral galaxies for measuring extragalactic distances depends on two main questions (Aaronson et al., 1981):

1. Do spiral galaxies follow a universal CM relation in the near-infrared;
2. Is the scatter less than what is observed in the optical?

In Sect. 1.3 the arguments in favour and against a universal CM relation for E/S0 galaxies have been discussed. A universal CM relation for E/S0 galaxies, over the entire wavelength range, seems to be likely, although the dispersion is expected to be considerable. Bower et al.'s (1992b) photometry allowed the CM relation for early-type galaxies to be used to estimate distances accurate to $\sim$20% per galaxy.

The main advantages of near-infrared observations are the relative insensitivity to contamination by the presence of young stellar populations and dust, for which it is necessary to correct in the blue passbands (see Sect. 2). The absorption corrections for dust in external galaxies, which are largest in the blue passbands, are difficult and controversial and therefore we were motivated to study the CM effect for our sample of edge-on disk galaxies (of types S0 to Sd) in the optical (red) / near-infrared regime, using $I-K$ colours and K-band absolute magnitudes.

In Sect. 2 we will discuss the nature of the observations we obtained to study the properties of edge-on disk galaxies, and discuss the various corrections that have to be applied for an accurate study of the optical/near-infrared CM relation.

We supplement our data with recently published I- and K-band data in Sect. 3 and discuss the similarities and differences, as well as the difficulties and uncertainties involved when comparing samples based on different selection criteria.

We will discuss our results in Sect. 4, in Sect. 5 a summary of our results and conclusions is given.

2 A dust-free CM relation

In Chapter 2, we described the selection of our sample of highly-inclined disk galaxies, the observations on which the analysis in this Chapter is based and the way we reduced our observational data (see also Peletier, 1993). We will confine ourselves here to summarize the selection criteria that were applied to the galaxies contained in the Surface Photometry Catalogue of the ESO-Uppsala Galaxies (ESO-LV; Lauberts & Valentijn, 1989):

- their inclinations are greater than or equal to 87°;
- the angular blue diameters (D_{25}^{B}) are larger than 2.′2;
- the galaxy types range from S0 to Sd, and
- they should be non-interacting and undisturbed.

In Chapter 2 we also discussed the reliability of our photometry in detail. From the detailed comparison of our photometry to previously published observations, our main conclusion is that, within the observational errors, our photometry is sufficiently accurate to be used for the analysis done in this Chapter.

Although our near-infrared observations are relatively insensitive to disturbing dust effects (see, e.g., de Grijs et al., 1997 [Chapter 8]), in general, three corrections have to be applied to the observed colours before they can be used to study the CM relation:

1. correction for colour gradients across a sample galaxy;
2. correction for Galactic reddening;
3. K-correction to the colours for the effects of redshift.

2.1 Colour gradients

Colour gradients in edge-on galaxies have not been studied extensively. In a few well-studied edge-on disk galaxies, colour gradients parallel to the major axis have been found to be negligible (e.g., Hamabe et al., 1980; Jensen & Thuan, 1982; van der Kruit & Searle, 1982) or to show an increasingly blue disk population with distance from the galaxy centre (e.g., Sasaki, 1987; Aoki et al., 1991), although the gradients were generally found to be small.

Vertical colour gradients in the disks of edge-on galaxies are generally small or negligible (see, e.g., de Grijs et al., 1997 [Chapter 8]); in fact, the vertical colour gradients are smaller than or of the same order as the observational errors for our I–K colour determinations. The only statistically significant variation along the minor axis is the reddening in the galaxy planes of our sample galaxies. This result is consistent with the observations of, e.g., Jensen & Thuan (1982) and van der Kruit & Searle (1982). As we showed in de Grijs & van der Kruit (1996, Chapter 4), the vertical scale height does not vary significantly as a function of wavelength, which indirectly shows the absence of any significant vertical colour gradient.

The colours we use in this Chapter were determined from the flat part of the vertical colour profile at the minor axis, to avoid the reddening caused by the in-plane dust. In de Grijs et al. (1997, Chapter 8) we show that, once away from the dust lane, the vertical I–K colour profiles are generally (nearly) flat and featureless, indicating that the excess extinction in the I band compared to the K band is negligible. Moreover, since young stellar populations are generally confined to regions close to the galaxy planes, an additional advantage of determining galaxy colours away from the planes is that the contamination by emission from these young stellar populations is greatly reduced or negligible.

Peletier & Balcells (1996) showed that the bulge colours on the minor axis and the inner disk colours taken in wedge apertures at 15° from the major axis at 2 K-band scale lengths are very similar. Therefore, a galaxy's colour determined in a relatively dust-free region at the minor axis can be considered as representative for the galaxy's dominant (old) stellar population, under the assumption that away from the galaxy planes colour gradients are small.

2.2 Galactic reddening

To deal with Galactic reddening, we used the Galactic extinction values in the I- and K'-bands, $A_{G,I}$ and $A_{G,K'}$, calculated from the $B-V$ colour excess predicted by Burstein & Heiles (1978, 1984) and using the Galactic extinction law (Rieke & Lebofsky, 1985):

$$A_{G,I}\,/A_{G,B} \;=\; 0.364 \pm 0.005\ ; \tag{1}$$
$$A_{G,K'}/A_{G,B} \;=\; 0.085 \pm 0.005\ , \tag{2}$$

thereby assuming that the Galactic extinction can be approximated by a foreground dust screen model.

De Vaucouleurs et al. (1991, RC3) claim that, except for a few heavily obscured galaxies, the difference between this mean extinction value and the more accurate value that can be determined for those galaxies that have directly measured colours is less than the uncertainty in the extinction values obtained from the Burstein & Heiles (1978, 1984) interpolation. This uncertainty is estimated at 0.06 mag for $A_{G,B} \le 0.6$ mag and at 0.10 for higher Galactic extinction estimates.

The Burstein & Heiles (1978, 1984) model predicts the Galactic reddening effects for Galactic latitudes $|b| > 10°$, based on local Galactic HI column densities. Burstein et al. (1987) presented some evidence that this prediction is a factor of 2 overestimated in the region $(\ell, b) = (230° < \ell < 310°, 10° < |b| < 20°)$. This concerns the following galaxies in our sample: ESO263-G15, ESO311-G12, ESO315-G20, ESO435-G14, ESO435-G25, and ESO564-G27. However, the effect in K' is small; for the two galaxies for which the effect is greatest, ESO263-G15 and ESO311-G12, it amounts to ~ 0.06 mag, whereas it involves an insignificant correction of order 0.00 – 0.03 mag for the others.

2.3 K-corrections and distance determinations

To correct for the effects of redshift, K-corrections have to be applied to the observed galaxy colours. In general, these corrections are small in the optical/near-infrared regime, however (e.g., Coleman et al., 1980; Schneider et al., 1983). The K-corrections for the I–K colours range from 0.00 – 0.04 for our sample galaxies (e.g., Schneider et al., 1983), depending on galaxy type (e.g., Coleman et al., 1980).

Heliocentric velocities for the majority of our sample galaxies were obtained by Mathewson et al. (1992), which provided us with a homogeneous data set to base our absolute magnitude calculations on. To obtain absolute magnitudes, we have to correct for the effects of the large-scale Hubble expansion. We used the formula for the systemic velocities adjusted for the solar motion with respect to the centroid of the Local Group given by Richter et al. (1987), which supposedly yields highly reliable values (Schmidt & Boller, 1992):

$$v_{LG} = v_{\odot} + \Delta v\ , \tag{3}$$

where

$$\Delta v = -49.59 \cos\ell \cos b \;+\; 306.95 \sin\ell \cos b \;-\; 18.59 \sin b \tag{4}$$

In Table 1 we give the heliocentric velocities, their corrections for motion with respect to the centroid of the Local Group, the apparent K-band magnitudes, the Galactic reddening factor in the K' band, the K-corrections, and the absolute K-band magnitudes, as well as the I–K colours.

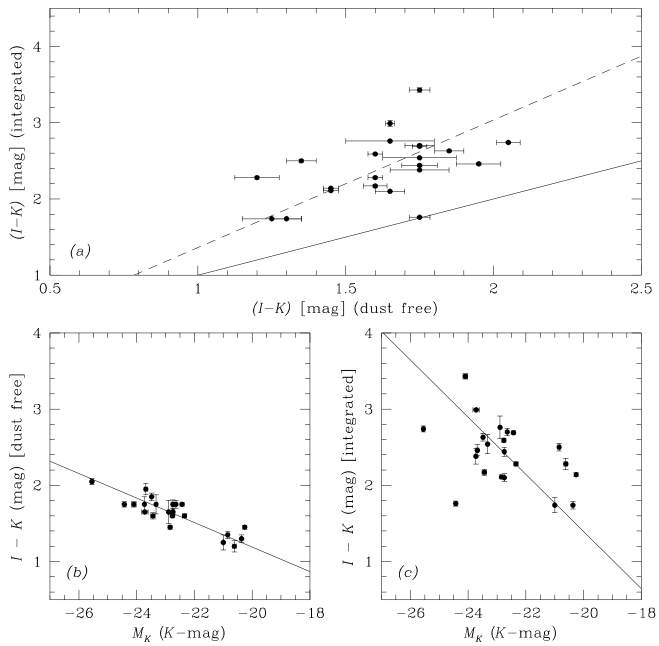

Fig. 1. *(a)* Comparison between the galaxy colours derived from the area outside the dust lane and their integrated counterparts. The dashed line gives and indication of the deviation of the integrated colours from the drawn line, which would be the locus of the points in the absence of contamination by dust; *(b)* and *(c)* Correlations between absolute K-band magnitude, M_K, and dust-free and integrated I–K colours, respectively. The mean optical/near-infrared colour-magnitude relation is indicated by the drawn line, for which the parameters are given in Table 2.

3 Comparison to literature samples

To assess the importance of contamination by dust, in Fig. 1*a*, we compare the galaxy colours derived from the essentially dust-free area away from the galaxy's midplane to the integrated colours, defined as the difference between the apparent total I and K-band magnitudes. From this figure, it is clear that the importance of dust should not be underestimated. The integrated colours are systematically redder than the "dust-free" colours, as is indicated by the deviation of the dashed line from the drawn line, which would be the locus of the points if there were no excess dust influence. Therefore, in published samples that contain highly-inclined galaxies, one should be cautious in interpreting the (optical/near-infrared) colours.

In Fig. 1*b* we have plotted the correlation between the "dust-free" I–K colour and the absolute K-band magnitude, M_K, which is well-defined. Fig. 1*c* shows the CM relation that would have resulted from using the integrated colours.

In Fig. 2 we compare our results with those published recently. Only very few samples with high-quality K-band observations have been published:

(a) The sample published by Bershady et al. (1994) and Bershady (1995) consists of 171 field galaxies of all types, selected from three high Galactic latitude fields, of which a subset of 143 is statistically representative in its sampling of the apparent colour distribution of galaxies.
(b) De Jong's (1996b) sample is a diameter-limited sample of 86 (nearly) face-on spiral galaxies.
(c) The data presented by Andredakis et al. (1995) and Peletier & Balcells (1997) consists of 37 field disk galaxies of types S0 to Sbc, uniform in orientation on the sky.
(d) Tully et al.'s (1996) sample was taken from the Ursa Major cluster; they present I and K'-band observations of a magnitude-limited sample of 70 disk galaxies.

The most significant differences from the data points derived from our sample are exhibited by samples *(a)* (Bershady et al., 1994; Bershady, 1995), and *(d)* (Tully et al., 1996).

In either of these samples the reddening due to dust is unknown. Bershady et al. (1994) and Bershady (1995) did not correct their integrated I and K-band colours for Galactic nor for internal extinction in their sample galaxies. Any comparison between our dust-free and their integrated colours would therefore show an additional discrepancy due to extinction effects. Tully et al. (1996), however, corrected their photometry for both Galactic foreground extinction and internal extinction, using Tully & Fouqué's (1985) inclination corrections. Although this method is useful to first order for low and intermediate inclinations, there are severe problems for highly-inclined galaxies.

Sample *(b)* (de Jong, 1996b) consists of disk-dominated (nearly) face-on galaxies. The face-on orientation ensures that the effects of internal extinction on the integrated I–K colours are small. De Jong (1996a) argues that the colours and colour gradients observed in his sample of face-on galaxies are determined by intrinsic physical processes in the disks rather than by extinction effects; the predicted extinction effects are not compatible with his observations. However, it is likely that the larger scatter in his CM relation compared to ours is at least partly due to extinction effects.

Finally, sample *(c)* (Andredakis et al., 1995; Peletier & Balcells, 1997) consists of early-type disk galaxies (S0 – Sbc), of which they studied the disk and bulge components separately. Peletier & Balcells (1997) assessed the importance of dust extinction by studying the change in the position of the galaxy centres as a function of wavelength. Such a shift occurs when a dust lane in front of the true centre obscures more light on one side of the centre than on the other, causing the observed centre to shift as a function of optical depth, or passband. The centre shift is in general within the typical errors, including the uncertainty of the determination of the luminosity peaks and the errors of alignment of their I and K-band images. Therefore, they concluded that dust extinction does not play a major role in their colour determinations.

In Table 2 we compare the slope and zero point of the optical/near-infrared CM relation derived from our sample of 24 edge-on disk galaxies with the CM parameters derived from the comparison samples in Fig. 2, as well as those obtained

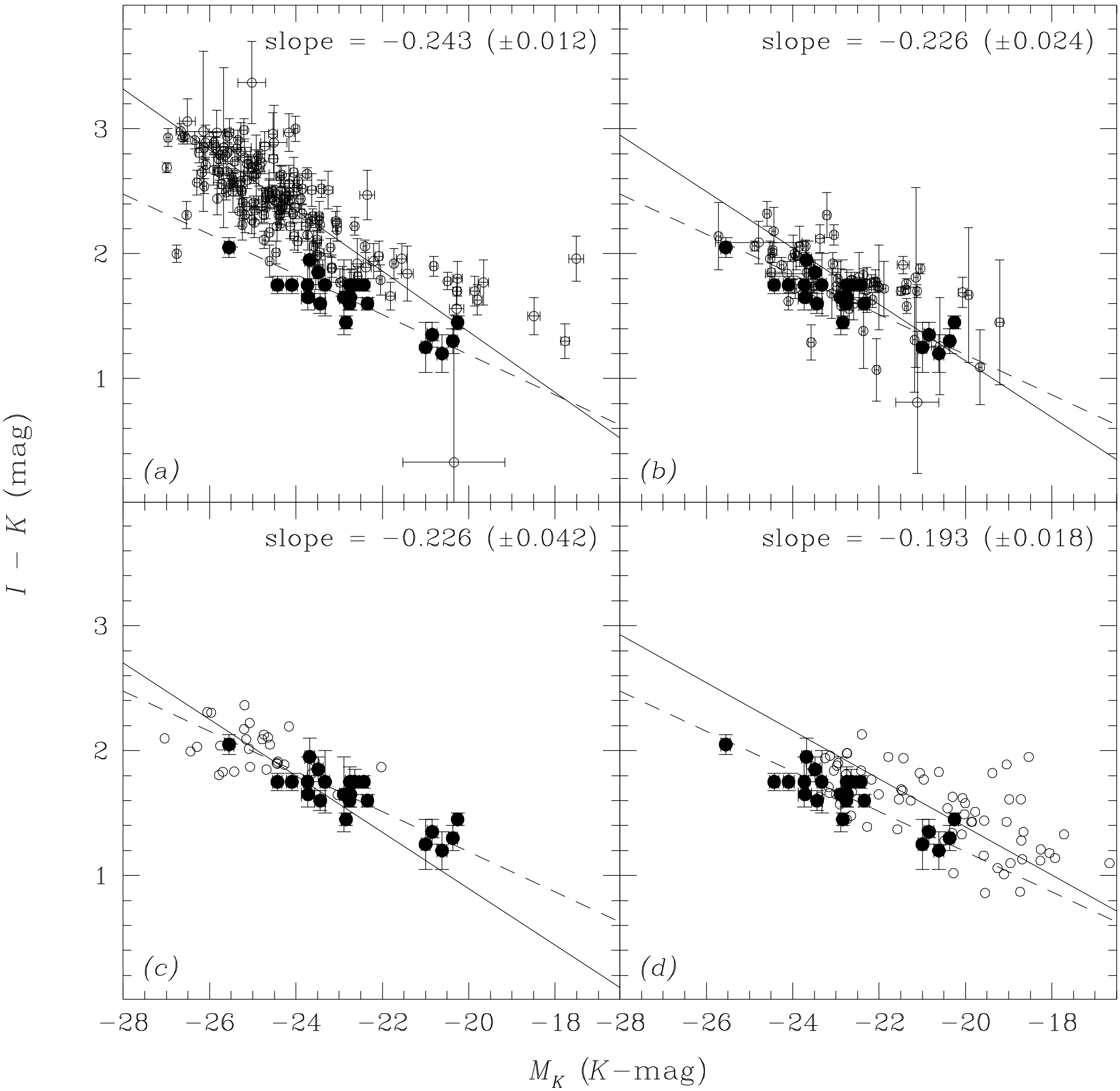

Fig. 2. Comparison of our M_K vs. *(I–K)* colour-magnitude relation with previously published data. The open circles represent previously published data; the filled circles show our sample galaxies. The mean optical/near-infrared colour-magnitude relations for the literature samples are indicated by the drawn line; for comparison, the dashed line represents the mean CM relation derived from the data presented in this Chapter. *(a)* Bershady et al. (1994), Bershady (1995); *(b)* de Jong (1996b); *(c)* Andredakis et al. (1995), Peletier & Balcells (1997); *(d)* Tully et al. (1996).

Table 1. Basic properties of the sample galaxies
Columns: (1) Galaxy name; (2) heliocentric velocity (taken from Mathewson et al., 1992); (3) velocity correction for motion w.r.t. the centroid of the Local Group (Richter et al., 1987); (4) and (5) apparent K-band magnitude and its observational error; (6) Galactic extinction in K'; (7) K-correction (interpolated from Schneider et al., 1980); (8) and (9) absolute K-band magnitude ($h = 1$) and its error; (10) and (11) I–K colour and its error.

Galaxy (1)	$v_\odot$ (km/s) (2)	Δv (km/s) (3)	m_K (mag) (4)	± (5)	$A_{G,K'}$ (mag) (6)	K-corr. (7)	M_K (mag) (8)	± (9)	I–K (10)	± (11)
ESO 026 G- 06	2748	−202.1	11.50	0.09	0.04	0.01	−20.37	0.01	1.30	0.10
ESO 141 G- 27	1922	−142.3	10.57	0.12	0.02	0.01	−20.26	0.01	1.45	0.05
ESO 142 G- 24	2119	−125.4	10.56	0.16	0.02	0.01	−21.00	0.02	1.25	0.20
ESO 157 G- 18	1268	−206.9	9.79	0.50	0.00	0.00	−20.85	0.05	1.35	0.10
ESO 201 G- 22	4014	−183.9	10.34	0.16	0.00	0.01	−22.89	0.02	1.65	0.30
ESO 263 G- 15	2525	−310.5	9.09	0.15	0.11	0.01	−22.74	0.02	1.65	0.10
ESO 286 G- 18	9162	−34.9	10.45	0.38	0.01	0.03	−24.43	0.04	1.75	0.07
ESO 311 G- 12	1128	−279.7	7.35	0.20	0.13	0.00	−22.43	0.02	1.75	0.05
ESO 315 G- 20	4843	−300.3	9.19	0.78	0.00	0.02	−24.10	0.08	1.75	0.07
ESO 340 G- 09	2546	−20.1	11.34	0.63	0.02	0.01	−20.62	0.06	1.20	0.15
ESO 358 G- 29	1776	−119.1	8.26	0.29	0.00	0.01	−22.84	0.03	1.45	0.05
ESO 383 G- 05	3637	−240.1	8.95	1.15	0.01	0.01	−23.72	0.12	1.65	0.03
ESO 416 G- 25	4998	−71.6	10.35	0.76	0.00	0.02	−23.44	0.08	1.60	0.08
ESO 435 G- 14	2697	−285.9	10.12	0.37	0.02	0.01	−22.75	0.04	1.75	0.12
ESO 435 G- 25	2470	−288.3	8.42	0.41	0.02	0.01	−23.48	0.04	1.85	0.10
ESO 437 G- 62	2850	−289.8	8.34	0.19	0.03	0.01	−23.73	0.02	1.75	0.20
ESO 446 G- 18	4843	−204.9	10.17	0.42	0.02	0.02	−23.33	0.04	1.75	0.25
ESO 446 G- 44	2793	−204.2	10.23	0.66	0.02	0.01	−22.34	0.07	1.60	0.05
ESO 460 G- 31	5759	25.3	10.02	0.56	0.06	0.02	−23.68	0.06	1.95	0.15
ESO 487 G- 02	1755	−153.8	8.84	0.39	0.00	0.01	−22.76	0.04	1.60	0.05
ESO 509 G- 19	10727	−218.9	9.58	0.44	0.02	0.04	−25.55	0.04	2.05	0.08
ESO 564 G- 27	2178	−259.4	9.72	0.34	0.05	0.01	−22.64	0.03	1.75	0.10

from supplementing our data with samples *(b)* and *(c)* (the "composite" CM relation).

Fig. 3 shows the composite optical/near-infrared CM relation, indicated by the dashed line. The best-fitting CM relation derived from our data alone is shown by the dotted line. The close agreement between both CM relations is an indication that we can indeed compare our observations to samples *(b)* and *(c)*. In fact, the good agreement between our sample and samples *(b)* and *(c)*, for all of which we can, to some degree, control the effects of dust extinction, leads us to suggest that *the optical/near-infrared CM relation for the old-disk population of spiral galaxies appears to be universal.*

Although, to first order, a linear fit is a good approximation to the data, there is a slight hint that the composite CM relation flattens towards the bright end. We have tried to investigate this trend by computing the mean I–K colours in absolute magnitude bins of 0.5 mag. The result is shown in Fig. 3 as the thick line; the errors indicate the dispersion in the data points in each bin. Although we are dealing with relatively few data points at the bright end of the optical/near-infrared CM relation, a flattening is indeed appreciated. This means that the brightest – or largest – disk galaxies have a roughly constant intrinsic I–K colour.

In Table 2 we also give the standard deviations of the observed data points with respect to the best fitting linear CM relation. The best-fitting correlation was determined by means of a bivariate minimization algorithm. The standard deviations define the scatter in the CM relations. It is immediately clear that the scatter in the CM relation determined from our dust-free data points is of order 40% smaller than for both samples *(b)* and *(c)*.

Table 2. Comparison of the optical/near-infrared CM parameters: $(I - K) = aM_K + b$
Columns: (1) Sample; (2) and (3) CM slope, a, and its error; (4) and (5) Intercept, b, and its error; (6) Scatter in the CM relation (σ).

Sample (1)	a (2)	± (3)	b (4)	± (5)	σ (mag) (6)
(a) Bershady	−0.243	0.013	−3.48	0.30	0.256
(b) de Jong	−0.226	0.024	−3.38	0.55	0.222
(c) Peletier	−0.226	0.042	−3.63	1.04	0.173
(d) Tully *(all)*	−0.193	0.018	−2.46	0.37	0.242
(d) Tully *($T \geq 4$)*	−0.199	0.025	−2.67	0.51	0.256
our (dust free)	−0.161	0.019	−2.03	0.43	0.119
our (integrated)	−0.375	0.080	−6.11	1.83	0.508
composite	−0.189	0.013	−2.59	0.31	0.205

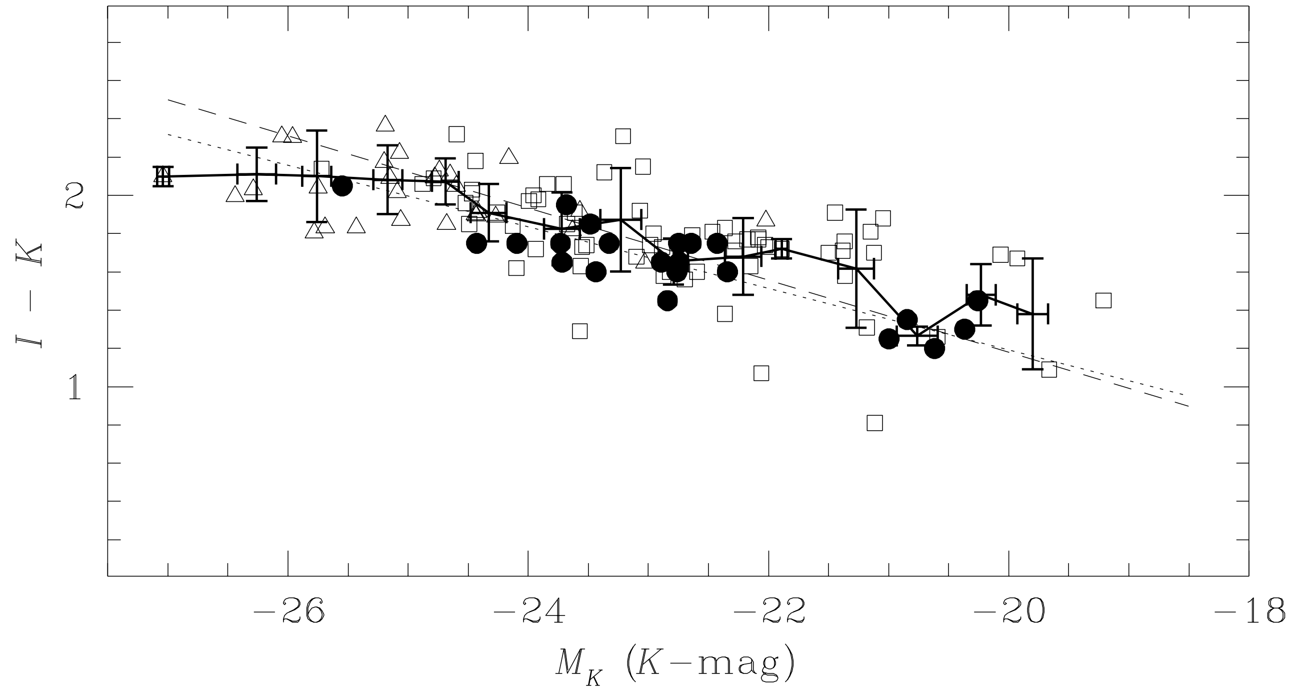

Fig. 3. Composite CM relation, derived from samples *(b)* and *(c)* and supplemented with the data presented in this Chapter. The open squares correspond to sample *(b)*, the open triangles to sample *(c)*. Our observations are shown as the filled circles. The best-fitting CM relation is indicated by the dashed line; its parameters are listed in Table 2. The optical/near-infrared CM relation derived from the data presented in this Chapter is indicated by the dotted line. The thick line was obtained by binning the data points in M_K bins of 0.5 mag; the errors indicate the dispersion in the data points in each bin.

4 Discussion

4.1 Applications of a tight CM relation

Only if we can put firm constraints on the scatter in the CM relation for (later-type) spiral galaxies, it may be useful as a (secondary) distance indicator. Therefore, we compared the scatter in the CM relation that we obtained from our dust-free disk colours to previous studies.

From a detailed photometric study of Virgo and Coma cluster members, Bower et al. (1992b) found that for elliptical galaxies the scatter in the CM relation is dominated by the observational errors. The inclusion of S0 and early-type spiral galaxies into their sample increases the observed scatter in the optical/near-infrared *(V–K)* CM relation.

To compare our results to those of Bower et al. (1992b), we applied the least-squares fitting technique we used to their data, and found close matches between our and their values for the r.m.s. scatter. Therefore, we can directly compare the values for the rms scatter obtained from our sample and the comparison samples taken from the literature (see Table 2) to Bower et al.'s (1992b) results.

Although it is obvious that the scatter in samples containing disk galaxies is significantly larger than in samples consisting of E/S0 galaxies only (see also Visvanathan & Sandage, 1977), we can conclude that by avoiding the disturbing effects of dust the scatter can be reduced significantly.

Therefore, *an optical/near-infrared CM relation for spiral galaxies based on dust-free colours may in principle be useful as a diagnostic to estimate distances in a statistical sense.* It provides independent distance estimates based on observational parameters.

For distance determinations to individual galaxies, we have to take into account the scatter in and the shallow slope of the CM relation, as well as the observational errors, which will result in relative distances accurate to $\sim 35\%$. This estimate is based on the observed scatter (i.e., the combination of observational and intrinsic scatter) in absolute *K* magnitude of ~ 0.7 mag. For a "typical" sample galaxy, the observational scatter in the absolute magnitude determinations (taking into account the uncertainties in the apparent magnitude and the correction for the motion with respect to the Local Group) is ~ 0.45 mag. This means that the intrinsic scatter among galaxies is ~ 0.5 mag.

Therefore, by obtaining high-quality observations of highly-inclined galaxies the accuracy of this method can be improved by reducing the observational scatter to a lower limit of order 0.02 mag (including the uncertainty in the distance determination). The accuracy will thus be limited by the intrinsic scatter in the optical/near-infrared CM relation (~ 0.5 mag). Because of this intrinsic scatter, the maximum accuracy of distance determinations that can be reached using this relation will be $\sim 25\%$.

Since the galaxies need to be spatially resolved, high-resolution observations done with the *Hubble Space Telescope (HST)* can provide a powerful tool to minimize the observational scatter and extend the useful distance range. Such observations may therefore provide the means to calibrate the relation.

The excess scatter (i.e., the scatter superposed on the observational scatter) in the CM relation for disk galaxies is most likely caused by the non-negligible effects of dust extinction, even at the z distances at which we determined our "dust-free" colours, and possibly non-negligible vertical colour gradients in the disks of our sample galaxies.

As opposed to the situation for elliptical galaxies, spiral galaxies cover a wide range in ages, metallicities, and star formation histories. In view of the variation of these parameters, it is even more surprising to find a very tightly constrained optical/near-infrared CM relation, in which the scatter is apparently dominated only by a galaxy's dust content. In de Grijs et al. (1997, Chapter 8) we discuss the dust properties of our sample galaxies and show the effects of extinction on the vertical colour profiles. In Peletier & de Grijs (1997) we will try to explain the differences between the CM relations for elliptical and spiral galaxies by studying the implications of different star formation histories among spiral and elliptical galaxies on the observed CM diagrams.

4.2 The shape of the CM relation

Lasker (1970) was the first to notice that the CM relation seems to flatten towards the brighter galaxies, although in Fig. 14 of de Vaucouleurs (1961) one can already see this effect. De Vaucouleurs (1961) remarks that there is a close correlation between colour and absolute magnitude for E/S0 galaxies in the Virgo cluster fainter than $M_V \approx -18$, but he did not notice a relative flattening at the bright end. Frogel et al. (1978) and Tully et al. (1982) also note that the V–K colour of the brightest galaxies is relatively independent of luminosity compared to the fainter groups.

With this relative flattening in mind, a linear fit to the CM relation may therefore not be the best representation of the correlation. However, flattening effects are second-order effects; to first order linear fits should be sufficient for the determination of distance moduli.

In the composite optical/near-infrared CM relation derived in Sect. 3 it was shown that the correlation seems to flatten towards the bright end, i.e., for galaxies with $M_K < -25.5$ the CM relation cannot be used as a diagnostic tool for distance determinations. At the faint end too few data points are available to draw firm conclusions about the shape of the CM relation, but it seems likely that the correlation is maintained down to galaxies as faint as $M_K \approx -20$.

4.3 The CM vs. Tully-Fisher relation

The key question raised by the results presented in Sect. 4.1 is how accurately one can determine distances, either to individual galaxies or to galaxy clusters, by using the optical/near-infrared dust-free CM relation compared to the Tully-Fisher distances (Tully & Fisher, 1977) derived from these observations.

Since we studied the CM relation in the optical/near-infrared regime, we also decided to study the I and K-band Tully-Fisher relation (TFR), i.e., the correlation between the absolute magnitudes and the maximum rotational velocities of our sample galaxies. For the majority of our sample galaxies a homogeneous data set containing both the maximum (optical) rotational velocities and total (apparent) I-band magnitudes were provided by Mathewson et al. (1992) and Mathewson & Ford (1996).

In Chapter 2, we compared our I-band photometry to that of Mathewson et al. (1992) and Mathewson & Ford (1996). From the detailed comparison of our photometry to theirs we showed that we can reproduce their results within the observational errors; since our total apparent I-band magnitudes also match theirs closely ($\langle m_{I,\mathrm{our}} - m_{I,\mathrm{Mathewson}} \rangle = -0.07 \pm 0.13$, see Chapter 5), we are confident that we can rely on our I-band photometry for the determination of absolute magnitudes.

The I and K-band TFRs derived from our data are shown in Fig. 4. To compare the accuracy of distances determined using these TFRs to those resulting from the optical/near-infrared CM relation, we determined the r.m.s. scatter in both relationships. In the I band, the observational scatter is 0.145 mag, which is of the same order as the observational scatter we determined from our CM relation in Sect. 4.1. In the K' band the observational scatter in our TFR is 0.296 mag.

We did not correct our integrated magnitudes for the effects of internal interstellar extinction; inclination corrections that aim to correct internal extinction are generally not applicable to highly inclined galaxies. Moreover, the amount of dust in a galaxy varies as a function of galaxy type, as well as among galaxies of the same type (see, e.g., Chapter 5; de Grijs et al., 1997 [Chapter 8], and references therein). Therefore, the observational scatter in the I and K-band TFRs derived from our observations is at least partly caused by internal extinction.

We are confident, however, that the scatter due to internal extinction is small, because of two reasons:

1. As we showed in de Grijs et al. (1997, Chapter 8), the K-band vertical surface brightness profiles exhibit hardly any signatures of either a regular dust lane or a patchy dust distribution, even in those galaxies having pronounced dust lanes (e.g., ESO383-G05, and ESO435-G25);
2. In Fig. 4 we show that the slopes of both the I and the K-band TFRs are similar. Differential extinction effects (i.e., excess extinction in the I band compared to the K band) would cause a shallower slope in the I-band TFR: for our B-band observations we found a TFR slope of -6.65 ± 0.49, and an observational scatter of 0.434 mag, based on a bivariate fit. On the other hand, the similar slopes in I and K could also mean that all galaxies suffer from approximately equal differential extinction (i.e., the extinction in I compared to the K-band extinction).

The observational errors in the I–K colours are therefore dominated by the photometric errors in the zero points, surface photometry and the extrapolation to total magnitudes, which are of order 0.08-0.10 mag. The remaining intrinsic scatter in the I band, where the scatter is least, is of order 0.11 mag. The scatter in the K-band TFR is significantly larger than in the I band. Bernstein et al. (1994) invoked population synthesis models to explain this behaviour. Such models suggest that, under the influence of metallicity variations, mass-to-light ratios of stellar populations are more stable in I than in the near-infrared (Worthey, 1994). However, the stellar population models of Vazdekis et al. (1996) do not confirm this result. Moreover, both the signal-to-noise ratio in our K'-band images is significantly lower and the effects of a varying sky background are much greater in K' than in the I-band observations, so that the errors, and thus the observational scatter, in the K-band magnitudes are larger.

The observational scatter that we find in the I-band TFR is small compared to that found in previous studies (for a discussion see Bernstein et al., 1994; Giovanelli et al., 1997): only Bernstein et al. (1994) reported a significantly smaller scatter, of $\sigma = 0.10$ mag, based on a sample of 22 galaxies. Giovanelli et al. (1997) argue that TF fits with scatter smaller than 0.25 mag are likely to be statistical accidents, which can occur when galaxy samples are small (e.g., Mathewson et al. [1992] for the Fornax cluster, and Bernstein et al. [1994] for the Coma cluster). This argument is based on the detailed study of the TFR for a large number of galaxies in 24 clusters. Giovanelli et al. (1997) determine the scatter in the I-band TFR for the individual clusters; their observational scatter varies between 0.12 and 0.36 mag, using bivariate fitting routines.

To our knowledge, to date studies of the TFR in the near-infrared K or K' band have not been published. Tully et al. (1996) obtained a large data set of Ursa Major cluster galaxies in the K' band, of which the characteristics, among which the TFR, are currently being analysed by Verheijen (1997). From Fig. 10 of Tully & Verheijen (1997), we derive a scatter of 0.531 mag in the K'-band TFR, based on a bivariate fit; for the low and high surface brightness galaxies in this figure, we derive a scatter of 0.654 and 0.363 mag, respectively. Compared to these data, the scatter in our data is significantly lower.

Giovanelli et al. (1997) applied a type-dependent correction for internal extinction to their observations, which varies between 0.50 and 1.00 mag in the I band; for the K band this would be a correction of 0.12 – 0.23 mag (assuming a K-band to I-band extinction factor of 0.23, see Eqs. (1) and (2)). If we apply a similar extinction correction to our data, we find a scatter in the I-band TFR of 0.225 mag (as opposed to 0.145 mag for the uncorrected measurements), and a scatter of 0.316 mag in the K-band TFR (compared to 0.296 mag before extinction correction). Although the scatter increases because of the extinction correction, it is still very small compared to the scatter in the I and K-band TFRs published previously.

In summary, the scatter in the optical/near-infrared "dust-free" CM relation is comparable to that in the I-band TFR, but it is of order twice as small as that in the K-band TFR, as determined from our observations. This shows the potential usefulness of the optical/near-infrared CM relation as a diagnostic tool for determining "statistical" distances and large-scale structures in the Universe. However, due to the shallower slope of the CM relation, the effects of errors in the distance estimates are relatively more important than for the TFR. Furthermore, space-based observations in the near-infrared may be able to reduce the observational scatter in the TFR (as well as that in the CM relation).

5 Summary and Conclusions

In this Chapter we have looked at the usefulness of the optical/near-infrared CM relation derived from dust-free colours as a diagnostic tool for secondary distance estimates. Our main conclusions are the following:

- Our data, supplemented with observations taken from the literature form a well-constrained composite CM relation; it appears that the optical/near-infrared CM relation for the old-disk population of spiral galaxies is universal.

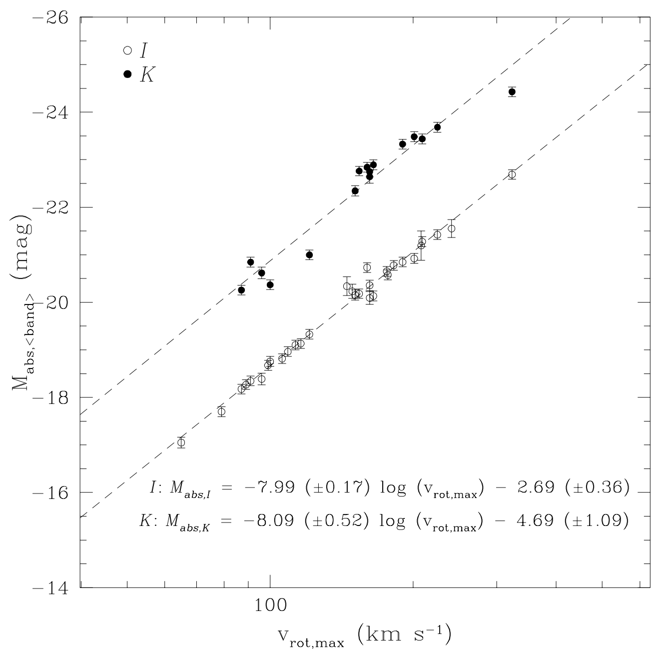

Fig. 4. I- and K-band TFRs derived from our observations (no extinction correction applied).

- By avoiding the disturbing effects of dust the scatter in the CM relation can be reduced significantly. Therefore, the optical/near-infrared CM relation for spiral galaxies, based on dust-free colours, may in principle be useful as a diagnostic tool to estimate distances in a statistical sense. Distances to individual galaxies can be determined with an accuracy of $\sim 35\%$. The intrinsic scatter in the K-band absolute magnitudes is of order 0.5 mag.
- High-resolution observations done with the *Hubble Space Telescope (HST)* can provide a powerful tool to extend the useful distance range and calibrate the relation.
- The observational scatter in the optical/near-infrared dust-free CM relation is comparable to that in the I-band TFR, but it is of order twice smaller than that in the K-band TFR.
- Although to first order a linear fit is a good approximation to the composite optical/near-infrared CM relation, the brightest disk galaxies (having $M_K < -25.5$) have roughly a constant intrinsic I–K colour. Our observations at the faint end of the CM relation are consistent with a linear correlation down to galaxies as faint as $M_K \approx -20$.

Acknowledgements - I would like to thank Reynier Peletier, Piet van der Kruit, Peter van Dokkum, Rob Swaters, Raja Guhathakurta and Andreas Just for the useful discussions that have resulted in this Chapter in its present form.

References

Aaronson, M., Cohen, J.G., Mould, J., Malkan, M., 1978, ApJ 223, 824

Aaronson, M., Persson, S.E., Frogel, J.A., 1981, ApJ 245, 18

Andredakis, Y.C., Peletier, R.F., Balcells, M., 1995, MNRAS 275, 874

Aoki, T.E., Hiromoto, N., Takami, H., Okamura, S., 1991, PASJ 43, 755
Arimoto, N., Yoshii, Y., 1987, A&A 173, 23
Balcells, M., Peletier, R.F., 1994, AJ 107, 135
Baum, W.A., 1959, PASP 71, 106
Bernstein, G.M., Guhathakurta, P., Raychaudhury, S., Giovanelli, R., Haynes, M.P., Herter, T., Vogt, N.P., 1994, AJ 107, 1962
Bershady, M.A., 1995, AJ 109, 87
Bershady, M.A., Hereld, M., Kron, R.G., Koo, D.C., Munn, J.A., Majewski, S.R., 1994, AJ 108, 870
Bower, R.G., Ellis, R.G., Rose, J.A., Sharples, R.M., 1990, AJ 99, 530
Bower, R.G., Lucey, J.R., Ellis, R.S., 1992a, MNRAS 254, 589
Bower, R.G., Lucey, J.R., Ellis, R.S., 1992b, MNRAS 254, 601
Burstein, D., 1977, in: The Evolution of Galaxies and Stellar Populations, eds. Tinsley, B.M., Larson, R.B., Yale University Observatory, New Haven, p. 191
Burstein, D., Davies, R.L., Dressler, A., Faber, S.M., Stone, R.P.S., Lynden-Bell, D., Terlevich, R.J., Wegner, G., 1987, ApJS 64, 601
Burstein, D., Heiles, C., 1978, ApJ 225, 40
Burstein, D., Heiles, C., 1984, ApJS 54, 33
Coleman, G.D., Wu, C.-C., Weedman, D.W., 1980, ApJS 43, 393
de Grijs, R., Peletier, R.F., van der Kruit, P.C., 1997, submitted to A&A **(Chapter 8)**
de Grijs, R., van der Kruit, P.C., 1996, A&AS 117, 19 **(Chapter 4)**
de Jong, R.S., 1996a, A&A 313, 377
de Jong, R.S., 1996b, Journal of Astronomical Data, Vol. 2 (http://www.vub.ac.be/STER/JAD/JAD.html)
de Vaucouleurs, G., 1961, ApJS 5, 233
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H.G., Jr., Buta, R.J., Paturel, G., Fouqué, P., 1991, Springer-Verlag, New York (RC3)
Ellis, R.S., Smail, I., Dressler, A., Couch, W.J., Oemler, A., Jr., Butcher, H., Sharples, R.M., 1997, ApJ 483, 582
Faber, S.M., 1977, in: The Evolution of Galaxies and Stellar Populations, eds. Tinsley, B.M., Larson, R.B., Yale University Observatory, New Haven, p. 157
Frogel, J.A., Persson, S.E., Aaronson, M., Matthews, K., 1978, ApJ 220, 75
Giovanelli, R., Haynes, M.P., Herter, T., Vogt, N.P., da Costa, L.N., Freudling, W., Salzer, J.J., Wegner, G., 1997, AJ 113, 53
Griersmith, D., 1980, AJ 85, 1295
Hamabe, M., Kodaira, K., Okamura, S., Takase, B., 1980, PASJ 32, 197
Jensen, E.B., Thuan, T.X., 1982, ApJS 50, 421
Larson, R.B., Tinsley, B.M., Caldwell, C.N., 1980, ApJ 237, 692
Lasker, B.M., 1970, AJ 75, 21
Lauberts, A., Valentijn, E.A., 1989, The Surface Photometry Catalogue of the ESO-Uppsala Galaxies, ESO **(ESO-LV)**
Mathews, W.G., Baker, J.C., 1971, ApJ 170, 241
Mathewson, D.S., Ford, V.L., Buchhorn, M., 1992, ApJS 81, 413
Mathewson, D.S., Ford, V.L., 1996, ApJS 107, 97 (AAS CD-ROM Series, Vol. 7)
Mobasher, B., Ellis, R.S., Sharples, R.M., 1986, MNRAS 223, 11
Peletier, R.F., 1993, A&A 271, 51
Peletier, R.F., Valentijn, E.A., Moorwood, A.F.M., Freudling, W., 1994, A&AS 108, 621
Peletier, R.F., Balcells, M., 1997, New Astr. 1, 349 (http://www1.elsevier.nl/journals/newast/jnl/articles/S138410769700002X/)
Peletier, R.F., de Grijs, R., 1997, in preparation
Richter, O.-G., Tammann, G.A., Huchtmeier, W.K., 1987, A&A 171, 33
Rieke, G.H., Lebofsky, M.J., 1985, ApJ 288, 618
Sandage, A., 1972, ApJ 176, 21
Sasaki, T., 1987, PASJ 39, 849
Schmidt, K.-H., Boller, T., 1992, Astron. Nachr. 313, 189
Schneider, D.P., Gunn, J.E., Hoessel, J.G., 1983, ApJ 264, 337
Tinsley, B.M., 1978, ApJ 222, 14
Tully, R.B., Fisher, J.R., 1977, A&A 54, 661
Tully, R.B., Mould, J.R., Aaronson, M., 1982, ApJ 257, 527
Tully, R.B., Fouqué, P., 1985, ApJS 58, 67
Tully, R.B., Verheijen, M.A.W., Pierce, M.J., Huang, J.-S., Wainscoat, R., 1996, AJ 112, 2471
Tully, R.B., Verheijen, M.A.W., 1997, ApJ 484, 145
van der Kruit, P.C., Searle, L., 1982, A&A 110, 61
Vazdekis, A., Casuso, E., Peletier, R.F., Beckman, J.E., 1996, ApJS 106, 307
Verheijen, M.A.W., 1997, Ph.D. thesis, Groningen University
Visvanathan, N., Sandage, A., 1977, ApJ 216, 214
Visvanathan, N., Griersmith, D., 1977, A&A 59, 317
Wyse, R.F.G., 1982, MNRAS 199, 1P