The scatter in the near-infrared colour-magnitude relation in spiral galaxies

R.F. Peletier¹,² and R. de Grijs³,²
¹ Dept. of Physics, University of Durham, South Road, Durham DH1 3LE, UK
² Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, The Netherlands
³ Astronomy Department, University of Virginia, PO Box 3818, Charlottesville, VA 22903-0818, USA

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ABSTRACT
We have determined a dust-free colour-magnitude (CM) relation for spiral galaxies, by using \( I - K \) colours in edge-on galaxies above the plane. We find that the scatter in this relation is small and approximately as large as can be explained by observational uncertainties. The slope of the near-IR CM relation is steeper for spirals than for elliptical galaxies. We suggest two possible explanations. First, the difference could be caused by vertical colour gradients in spiral galaxies. In that case these gradients should be similar for all galaxies, on average \( \sim 0.15 \) dex in \([\text{Fe}]/[\text{H}]\) per scale height, and increase for later galaxy types. The most likely explanation, however, is that spirals and ellipticals have intrinsically different CM relations. This means that the stars in spirals are younger than those in ellipticals. The age, however, or the fraction of young stars in spiral galaxies, would be determined solely by the galaxy’s luminosity, and not by its environment.

1 INTRODUCTION
Baum (1959) and de Vaucouleurs (1961) first established that early-type galaxies obey a tightly constrained colour – absolute magnitude (CM) relation. Somewhat later, in 1978, Sandage & Visvanathan first proposed that the relation, if applied to galaxy clusters, could provide a significant constraint on their past history of star formation. Using modern detectors Bower et al. (1992a,b) determined that both in Virgo and Coma the scatter around the CM relations in \( U - V \), \( B - V \) and \( V - K \) is extremely small (\( \leq 0.05 \) mag), comparable to their observational uncertainties (\( \sim 0.03 \) mag). This allowed them to put strong constraints on the age scatter of early-type galaxies in clusters. Recently, Ellis et al. (1997) again found very small scatter in the CM diagram of early-type galaxies in clusters at \( z \sim 0.54 \), which led them to conclude that most of the star formation in these clusters must have ended at \( z \sim 3 \). These and other observations have led people to attribute the origin of the CM relation to changes in metallicity, caused by the fact that the larger galaxies have larger binding energies, so that the gas can be enriched to higher metallicities (e.g., Mathews & Baker, 1971; Faber, 1977; Arimoto & Yoshii, 1987).

For spiral galaxies, however, the situation is much more complicated, because of recent star formation, as well as extinction by dust. Visvanathan & Griersmith (1977) found for early-type spiral galaxies in the Virgo cluster (S0/a to Sab) within the errors the same optical CM relation as had been found for E/S0 galaxies, except that the scatter was larger. Later Tully et al. (1982) and Mobasher et al. (1986) established optical-IR and IR CM relations for early and late type spirals, with considerable scatter. Tully et al. (1982) claimed that the difference between early and late type spirals could be explained by the presence of more star formation in late type spirals, affecting especially the blue light, and hence the \( B - H \) colour. In the last decade this picture has not changed very much. Interpreting a CM relation using the \( B - H \) colour is extremely complicated, given the fact that the effects of star formation and extinction counteract each other. Valentijn (1990) and afterwards many others authors have shown that the extinction corrections applied by Tully et al. are a factor of 2 or 3 too low, but in any case very uncertain. To be able to draw more detailed conclusions about galaxy formation and evolution, a different way of presenting the CM relation has to be found. In this paper we argue that this can be done using the \( I - K \) colour, obtained at positions in the galaxy that are likely to be very little affected by dust extinction. The main difference with previous work is that we use local colours here, which is now possible due to advances in IR detector technology. Integrated colours from, e.g., aperture photometry are very hard to interpret due to the complicating effects of extinction and stellar population differences, except if the colours do not change much inside
the galaxy, as is the case in elliptical galaxies. Secondly, to eliminate the effects of very recent star formation as much as possible, we have tried to use a colour that is as red as possible, while trying to keep the wavelength baseline large. Knapen et al. (1995) show convincingly that the $I - K$ colour is predominantly a dust/extinction indicator, while recent star formation shows up much less than in a blue colour like $B - V$.

In this paper we try to use the $I - K$ vs. $M_K$ relation to determine a colour-magnitude relation with as low a scatter as possible for spiral galaxies. This relation can be used to study the following problems: 1) The nature of spiral galaxies themselves. By comparing spirals with ellipticals we can study the star formation history of spirals in a very direct way, making only the simple assumption that elliptical galaxies are coeval (see, e.g., Kodama et al. 1998). 2) The role of the environment on the evolution of galaxies. A tight CM relation for spirals can serve as a very useful tool to study the evolution of spiral galaxies and the role of their environment and 3) The use of the CM diagram as a distance indicator, very useful for isolated galaxies in the field (de Grijs & Peletier, in preparation).

In the following section we present the data used for our CM relation. In section 3 the scatter on the relation is discussed, and a comparison is made with early-type galaxies. In section 4 we discuss some implications of the low scatter for the nature of spiral galaxies, after which we summarise the paper.

2 A DUST-FREE CM RELATION

To determine a dust-free CM diagram we decided to limit ourselves to two datasets, of which we can be fairly confident that the amount of extinction by dust is very small. The first is a sample of 22 edge-on galaxies, described in de Grijs et al. (1997). This is a random subsample of Southern non-interacting galaxies with inclinations larger than $87^\circ$ and blue diameters $D_B^B$ larger than $2.2$. These galaxies were observed in $I$ and $K$. More observational details can be found in de Grijs (1998). It was found that although the central regions are heavily obscured, the vertical colour profiles are symmetric, featureless and with colour almost constant as a function of radius (de Grijs et al. 1997). These 3 properties together indicate that the colours here are not reddened by dust. We therefore took the average of the colour on both sides of the galaxy in the region where the colour profile is featureless. Absolute $K$-magnitudes were determined using a simple Hubble flow model correcting for the motion of the local group (see de Grijs 1997). The second sample is the sample of early-type spiral galaxies of Peletier & Balcells (1997). This is a sample of galaxies with inclinations larger than $50^\circ$, for which the colours were determined in the bulge opposite to the dustlane. The fact that the colour profiles on one side of the galaxy generally are featureless shows that our assumption about negligible extinction is justified. However, since for some of the latest-type galaxies of this sample the bulges are small, and therefore their colours probably more affected by extinction, we only consider the earliest-type spirals (type $\leq 1$) for the analysis done in this paper. Other samples are available (e.g., de Jong 1996), but less is known about their extinction properties, and by including them the scatter generally increases.

The colours of both samples used were corrected for Galactic extinction and redshift in the way described in Balcells & Peletier (1994), Peletier & Balcells (1997) and de Grijs (1997). Both corrections are small (resp. $\leq 0.10$ and $\leq 0.04$ for $I - K$), because infrared colours of nearby galaxies are generally not very sensitive to these corrections.

In order to compare these colours with central aperture measurements of ellipticals, a correction for internal colour gradients should be made. The colours of the sample of Peletier & Balcells (1997) were taken on the minor axis in the bulge at 0.5 effective bulge radii. Peletier & Balcells (1996) and also Terndrup et al. (1994) show that for their sample the colour difference in $I - K$ between the bulge and the inner disk (2 exponential scale lengths) is very small ($0.07 \pm 0.15$ mag (Peletier & Balcells 1996)), indicating small stellar population differences. For the edge-on galaxies of de Grijs et al. (1997) the colours were taken at an average height above the plane of 2 scale heights. Very little is known about vertical colour gradients in spirals. In our Galaxy Trefzger et al. (1995) find a vertical metallicity gradient of $\Delta [Fe/H]/\Delta h_z = 0.05$, using $h_z = 247$ pc (Kent et al. 1991). Using simple stellar population models (e.g. Vazdekis et al. 1996), this corresponds to $\Delta (I - K)/\Delta h_z = 0.025$. For external galaxies at present no data is available for vertical stellar population gradients. Radial colour gradients are small as well - for the sample of Peletier & Balcells (1997) we find an average $R - K$ gradient of 0.12 mag per scale length, and a scatter of 0.11 mag. This corresponds to an $I - K$ gradient of about 0.10 mag/scale length. Some simple modelling shows that we need to correct our colours by $\leq 0.075$ mag to make them compatible with those of Bower et al. (1992a). Since we do not know how vertical colour gradients vary as a function of morphological type, we would have to apply the same correction for each galaxy, and therefore the slope of the CM relation in spirals would not change. For this reason finally the correction for internal stellar population gradients was not applied.

3 THE SCATTER IN THE CM RELATION, AND COMPARISON WITH EARLY-TYPE GALAXIES

In Fig. 1 we show the CM relation for our 2 samples. The drawn line is the least squares fit. We have also plotted the elliptical and S0 galaxies from Bower et al. (1992a), for which they found that the scatter was comparable with the observational uncertainties. Since these authors do not have $I - K$ colours, we have converted their $V - K$ to $I - K$ using the models of Vazdekis et al. (1996). To do so we have made a linear fit of $I - K$ as a function of $V - K$ for all single-age, single-metallicity models presented. Similar results are obtained if other stellar population models (e.g., Worthey 1994) are used. Note that a sequence in morphological types can be seen in Fig. 1, with the latest type spirals (filled circles) the faintest and the bluest.

In Table 1 the best-fitting least squares fits are given. For our spiral galaxies we have applied a bivariate fitting routine, taking into account errors in both directions (see Peletier & Willmer 1993). The uncertainties in our photon-
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3 showed that bulges of early-type spirals and S0s in $U - R$, $B - R$ and $R - I$ are always bluer or have the same colour as ellipticals of the same luminosity, and therefore these S0 galaxies must be affected considerably by extinction (at least $A_B = 0.5$ mag), which seems to be in conflict with the very small scatter among the S0 galaxies. Secondly, there is a considerable gap of about 0.5 mag between the S0 galaxies and the early-type spirals, also unlikely from other work. Similarly, the relation of Wyse (1982) for spirals is probably severely affected by extinction, since her brightest galaxies have $B - H$ values around 5, much redder than the reddest nearby ellipticals without dust. In any case, much better interpretable and understandable is the work of Mobasher et al. (1986). They present CM relations in infrared ($I - K$) and optical-infrared ($B - K$) colours for spirals and ellipticals. In both bands the relation for spirals is steeper than that for ellipticals, although in the IR this difference is not very significant. Their result, although with large scatter, is largely consistent with our results presented here.

From Table 1 one can see that the scatter in the CM relation for spirals is very small (0.07 mag after taking into account the observational errors, or possibly less, since this number is smaller than the average observational error). Also, this relation falls about 0.1 – 0.4 mag below the CM relation for ellipticals, and has a steeper slope. Here we present two possible explanations for the difference between the two CM relations.

(i) While elliptical galaxies show very little or no star formation, and have at most 10% of their stars formed in the last 5 Gyr (Bower et al. 1992b), all spiral galaxies are currently forming stars, whereby the rate of star formation is determined only by the infrared luminosity (or mass) of the galaxy.

(ii) Spiral galaxies in general have considerable vertical colour gradients. In this case we deduce that the vertical gradient per scale height needs to be about 0.15 dex in [Fe/H], if the dust-free CM relation is the same for ellipticals and spirals. Later type spirals need to have larger gradients than earlier types.

In the first case, the most straightforward explanation for the origin of both relations would be that they are driven by metallicity, but that the bluer $I - K$ colours are due to a small amount of recent star formation, that does not change the metallicity significantly, but affects the colours, and somewhat brightens the galaxy. In Fig. 2 we show a grid of Single Stellar Population (SSP) models of Bruzual & Charlot (1998) for metallicities between 0.004 and solar and ages between 0.1 and 20 Gyr. We have assumed that the ellipticals are 20 Gyr old and lie on the CM relation, and have followed this relation in time. Although the assumption that stars in a spiral galaxy are coeval is almost certainly too simple, the figure shows that on average the stars in late-type spirals are much younger than in ellipticals. The models here show ages $\leq 1$ Gyr, although one can find other numbers if e.g. models with exponentially decreasing star formation are used. The most interesting aspect of this work is that we find that the scatter in the CM relation for spirals is very small, and that there is a gap between spirals and ellipticals. This means that the current star formation in a spiral galaxy is determined by its size, morphological type or luminosity, and probably not by its environment or

<table>
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<th>E/S0</th>
<th>Sp</th>
<th>intercept</th>
<th>slope</th>
<th>(1)</th>
<th>(2)</th>
</tr>
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<tbody>
<tr>
<td>2.053 ± 0.008</td>
<td>1.913 ± 0.030</td>
<td>-0.0438</td>
<td>-0.1173</td>
<td>0.0041</td>
<td>0.0133</td>
</tr>
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Figure 1. The $I - K$ vs $M_K$ relation as discussed in this paper. Plotted are the data from Peletier & Balcells (1997) with type earlier than 1.5 (filled squares). The galaxies of de Grijs et al. (1997) are plotted as filled triangles for types earlier than 5.5 and as crosses for later types. The elliptical/S0 galaxies from Bower et al. (1997) are plotted as open circles.

Table 1. CM relations ($I - K = a + b(M_K + 25)$) and scatter for ellipticals and spirals. (1) gives the measured scatter in magnitudes, and (2) the scatter after correcting for observational uncertainties.

4 DISCUSSION

Although the scatter that we find in the CM relation for spiral galaxies is much smaller than the values that have appeared in the literature until now, the results are consistent. Tully et al. (1982) already showed that spiral galaxies obey a CM relation, similar to the one found for ellipticals. They found that S0 galaxies occupy a completely different region on the ($B_T$ – $H_{0.5}$) CM plane than the later type spirals. This result, however, is peculiar for two reasons. First, some of the S0 galaxies are redder than the bright elliptical galaxies presented in the same paper. Balcells & Peletier (1994)
interactions, without much scatter. The CM relation can be better understood by comparing it to the large compilation of spiral galaxies by McGaugh & de Blok (1997), who show that fainter galaxies generally have lower surface brightness, bluer optical colours, and increasing gas mass fractions, as a consequence of which it is likely that their average ages are also younger.

Now, let us assume that spiral galaxies have the same $I - K$ CM relation as ellipticals, but that the difference we observe here is solely caused by vertical stellar population gradients in spiral galaxies. There are two reasons why we argue that this option is not very likely. First, the vertical metallicity gradient in our Galaxy, the only place where such a quantity has been measured at present, would correspond to only 0.025 mag per scale height in $I - K$, which is by far not enough to explain the difference between spirals and ellipticals. Secondly, the gradients would have to be larger for smaller galaxies, whereas the scatter between the spirals of the same luminosity would still need to remain very small. De Jong (1996) shows that radial colour gradients for the later types are not larger than those for larger, early-type spirals. For this reason it is not expected that the behavior in the vertical direction would be completely different.

5 CONCLUSIONS

The main results of this paper are as follows:

- We have determined a dust-free CM relation for spiral galaxies, by using $I - K$ colours in edge-on galaxies above the plane. We find that the scatter in this relation is small and approximately as large as can be explained by observational uncertainties. The slope of the IR CM-relation is steeper for spirals than for elliptical galaxies.

- We present two possible explanations. First, the difference could be caused by vertical colour gradients in spiral galaxies. In that case these gradients should be similar from galaxy to galaxy, have an average size of about 0.15 dex in [Fe/H] per scale height, and increase for later galaxy types. The other, much more likely, possibility is that spirals and ellipticals have different CM relations. The difference is caused by current star formation, which has to be present in all spirals, as opposed to ellipticals. The amount of current star formation would depend only on the galaxy’s infrared luminosity, and not on its environment.

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