On the CCD calibration of Zwicky galaxy magnitudes and the properties of nearby field galaxies

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Abstract

We present CCD (charge-coupled device) photometry for galaxies around 204 bright ($m_Z < 15.5$) Zwicky galaxies in the equatorial extension of the APM Galaxy Survey, sampling an area over 400 $\text{deg}^2$, which extends 6 $h$ in right ascension. We fit a best linear relation between the Zwicky magnitude system, $m_Z$, and the CCD photometry, $B_{\text{CCD}}$, by doing a likelihood analysis that corrects for Malmquist bias. This fit yields a mean scale error in Zwicky of $0.38 \text{ mag} \text{ mag}^{-1}$; i.e. $\Delta m_Z = (0.62 \pm 0.05) \Delta B_{\text{CCD}}$ and a mean zero-point of $(B_{\text{CCD}} - m_Z) = -0.35 \pm 0.15 \text{ mag}$. The scatter around this fit is about 0.4 mag. Correcting the Zwicky magnitude system with the best-fitting model results in a 60 per cent lower normalization and 0.35-mag brighter $M_\odot$ in the luminosity function. This brings the CfA2 luminosity function closer to the other low-redshift estimations (e.g. Stromlo-APM or LCRS). We find a significant positive angular correlation of magnitudes and position in the sky at scales smaller than about 5 arcmin, which corresponds to a mean separation of $120 h^{-1} \text{kpc}$. We also present colours, sizes and ellipticities for galaxies in our fields, which provides a good local reference for the studies of galaxy evolution.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: fundamental parameters – large-scale structure of Universe

1 INTRODUCTION

Some important aspects of galaxy evolution can only be understood by studying the statistical properties of nearby field galaxies, in particular its luminosity function (LF). As well as providing vital information for galaxy evolution studies, an accurate knowledge of the present-day LF is needed to normalize the number counts of galaxies at fainter magnitudes, and to understand the clustering and large-scale structure of the galaxy distribution. Moreover, the colour distribution of the nearby galaxies provides a basic reference to determine star formation rates in galaxies.

Much recent work has been directed towards studying the evolution of the LF using samples of faint galaxies at high redshift, but a consideration of the ensemble of available estimates of the LF at low redshifts suggests that there are still large inconsistencies that must be reconciled before reliable conclusions can be drawn about the implications of deep surveys.

It is common practice to fit the LF to the so-called Schechter (1976) form:

$$\phi(L) = \phi_\ast \left( \frac{L}{L_\ast} \right)^\alpha \exp \left( - \frac{L}{L_\ast} \right).$$

where luminosity is related with magnitude in the usual way, $L/L_\ast = 10^{0.4(M_\ast - M)}$. Determinations of the low-redshift $B$-band LF are available from the Stromlo-APM Survey (SAPM; Loveday et al. 1992), the Southern Sky Redshift Survey (SSRS: Da Costa et al. 1994), the CfA2 redshift survey (Marzke, Huchra & Geller 1994), and more recently from the ESO Slice Project (Zucca et al. 1997) and the 2dF Galaxy Redshift Survey (Folkes et al. 1999). Determinations in the $R$ band are available from the Las Campanas Redshift Survey (LCRS; Lin et al. 1994) and from the Century Survey (CS; Geller et al. 1997). The best determinations of the Schechter function parameters from each of these surveys are listed in Table 1. The SSRS2 is based on the ESO-Uppsala photometry of Lauberts & Valentijn (1989), but transformed to the $B(0)$ system of Huchra (1976). Da Costa et al. (1994) ascribe the difference in the LFs of the two surveys to the large colour term used by Lauberts & Valentijn to relate the two systems, and so we therefore use $m_Z$ for Zwicky magnitudes and $B(0)$ for SSRS2 magnitudes. Da Costa et al. (1994) quote the rms difference between $B(0)$ and $b_j$ as $\leq 0.2 \text{ mag}$. We quote the results for the red LFs of the Las Campanas and Century surveys here for completeness, and do not concern ourselves with the details of the transformations between red and blue passbands. We note however that Geller et al. (1997) find the
prediction based on colour transformations applied to the SSRS2 LF obtained from the CS to be in excellent agreement with a $M$ function of absolute magnitudes

Luminosity function estimations in the SAPM and the CfA2 as a function of absolute magnitudes $M$ in each magnitude system ($b_1$ or $m_2$). The continuous lines enclose the $2\sigma$ region in the SAPM estimation, whereas the dashed lines enclose the $2\sigma$ region in the CfA2 estimate.

Table 1. Luminosity function parameters derived from currently available surveys.

| Survey | Band | $N_{gal}$ | $\xi$ | $M_\alpha$ | $\alpha$ | $\phi_\alpha$ $(h^3$ Mpc$^{-3}$) |
|--------|------|----------|------|-----------|--------|-----------------|
| CfA2   | $m_2$| 9063     | 0.025| $-18.8 \pm 0.3$ | $-1.0 \pm 0.2$ | 0.040 $\pm$ 0.01 |
| SSRS2  | $B(0)$| 2919     | 0.025| $-19.5 \pm 0.08$ | $-1.2 \pm 0.07$ | 0.015 $\pm$ 0.003 |
| SAPM   | $b_1$| 1658     | 0.050| $-19.5 \pm 0.13$ | $-1.0 \pm 0.15$ | 0.014 $\pm$ 0.002 |
| ESP    | $b_1$| 3342     | 0.1  | $-19.6 \pm 0.07$ | $-1.2 \pm 0.06$ | 0.020 $\pm$ 0.004 |
| 2dF    | $b_1$| 5869     | 0.1  | $-19.7 \pm 0.06$ | $-1.3 \pm 0.05$ | 0.017 $\pm$ 0.002 |
| LCRS   | $r$  | 18678    | 0.1  | $-20.3 \pm 0.02$ | $-0.7 \pm 0.05$ | 0.019 $\pm$ 0.001 |
| CS     | $R_{K\ell}$| 1762    | 0.06 | $-20.7 \pm 0.2$ | $-1.2 \pm 0.2$  | 0.025 $\pm$ 0.006 |

Figure 1. Luminosity function estimations in the SAPM and the CfA2 as a function of absolute magnitudes $M$ in each magnitude system ($b_1$ or $m_2$). The continuous lines enclose the $2\sigma$ region in the SAPM estimation, whereas the dashed lines enclose the $2\sigma$ region in the CfA2 estimate.

At face value, the CfA2 LF seems to have less intrinsically bright galaxies (at least 10 times less $M = -21$ galaxies). Of course, this depends on the transformation between Zwicky $m_2$, APM $b_1$ or LCRS $R$ magnitudes. Efstathiou, Ellis & Peterson (1988) adopted the relation $m_2 = B + 0.29$ for the CfA1 survey (Huchra et al. 1983). This transformation would move the CfA2 LF in the correct direction to reconcile it with other measurements, although Lin et al. (1994) point out that a shift of 0.7 mag in $M$ is required to reconcile $M_\alpha$ with the other surveys. However, a simple shift in the magnitude zero-point would not correct for the apparent discrepancy in the normalization, which would suggest that a more subtle effect is present in the CfA2 data.

In this paper we present the results of a photometric survey of bright galaxies in the overlap region of CfA2 and the equatorial extension of the APM Galaxy Survey (Maddox et al. 1990a,b, 1991), which we will use to investigate this apparent discrepancy. In Section 2 we begin by comparing the APM photometry with the Zwicky measurements. We describe our CCD observations in Section 3, and compare our observations with Zwicky’s photometry in Section 4. In Section 5 we give some other properties for the galaxies in our fields and discuss the implications for the LF. In Section 6 we compare our results with the findings of other authors and discuss the possible implications for other results. No direct CCD calibration has yet been published for this part of the APM Galaxy Survey. We will present a detailed comparison of our CCD photometry with the APM data down to the survey completeness limit in a separate paper.

2 A COMPARISON OF ZWICKY AND APM magnitudes

From the information used to calibrate the APM survey we would expect $B = b_1^{APM} + 0.2$, given the mean $(B - V) \sim 0.7$ and the colour equation $b_1 = B - 0.28(B - V)$ (Blair & Gilmore 1982; Maddox et al. 1990b) – although this shift could increase by as much as 0.07 mag according to the findings of Metcalfe, Fong & Shanks (1995). Adopting the relation between $m_2$ and $B$ used by Efstathiou et al. (1988), this transformation would imply

$$m_2 = b_1 + 0.5,$$

(2)

which is close to the shift in $M_\alpha$ adopted by Lin et al. (1994), and, if taken as they stand, would suggest that the results of the two surveys might be consistent, at least in $M_\alpha$.

We investigated the usefulness of this relation by considering the subset of $\sim 100$ galaxies found in the part of the APM Galaxy Survey equatorial extension which overlaps with the southernmost region of CfA2 (the $S + 3$ sample of Marzke et al. 1994). This sample is drawn entirely from volume V of the Zwicky catalogue (Zwicky et al. 1968). We have used the publicly available CfA1 catalogue as our source for Zwicky galaxies, with magnitudes corrected as described in CfA1. The CfA1 includes redshifts only for galaxies with $m_2 < 14.5$, but has magnitudes and positions for $m_2 < 15.5$. Marzke et al. find this sample to be representative of the whole of the southern part of CfA2 (their fig. 3). We inspected this sample of galaxies on the film copies of the UKST IIIa-J Sky Survey plates, and examined the image maps as reconstructed from the APM survey data. We removed from our sample all those galaxies which either had been broken up into multiple image components or were composed of multiple components that had been merged into a single object by the APM software. The distribution of these objects in the $m_2, b_1$ plane is shown in Fig. 2. A simple least-squares fit to these data with the slope constrained to be unity gives a zero-point shift of

$$m_2 = b_1 - 0.6 \pm 0.5,$$

(3)

which is more than a magnitude in the opposite sense to that implied by equation (2). As will be noted below, a detailed calibration requires a correction for Malmquist bias.

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The APM Survey is internally calibrated by matching images in plate overlaps, with the overall zero-point fixed by a number of CCD frames distributed over the survey region (Maddox et al. 1990b). At bright magnitudes (b_J ≤ 17) the calibrations are less well determined owing to a combination of variations in galaxy surface brightness profiles and the smaller number of bright galaxies found in the plate overlap regions. The equatorial survey extension has been calibrated by matching to the original survey using plate overlaps and the adopted zero-point for the whole survey taken from the original CCD photometry. Maddox et al. (1990b) also used their CCD frames to perform an internal consistency check on the quality of the plate–plate matching technique, and found the residual zero-point errors on individual plates to be ≤0.04 mag. The individual uncertainties in galaxy magnitudes in the APM system are therefore expected to be much smaller than the effect shown in Fig. 2. It is possible that an improvement in the quality of the plate material used for the more recent plates of the equatorial extension coupled with changes in the plate copying process could result in a small change in the saturation correction required for bright galaxies, and that this could produce an effect in this direction (Maddox, private communication). However, account was taken of such effects in the construction of the equatorial extension, and any residual effect is likely to be much smaller than the discrepancy shown here.

The transformation of Zwicky magnitudes to B deduced by Efstathiou et al. (1988) are based on a comparison of the CfA1 survey data with the Durham–AAT redshift survey using 139 galaxies (Peterson et al. 1986). These authors find that the different volumes of the Zwicky catalogue have large variations in the zero-points, although volume V is found to be representative of the calibration as estimated from all volumes. These data are limited to m_Z < 14.5, and the luminosity function parameters inferred for the CfA1 are consistent with the parameters listed for the other surveys in Table 1. It is not possible to draw a direct comparison of the APM data with Zwicky data brighter than m_Z ~ 14, because of heavy saturation of galaxies this bright in the APM data. The most plausible inference from the comparison described above would therefore be a difference in the magnitude scales of the two surveys for b_J ≥ 14, with the calibration of Efstathiou et al. (1988) being appropriate for the Zwicky system at brighter magnitudes.

3 CCD DATA

3.1 Observations

We used the galaxies from the sample discussed in the previous section as the basis for a CCD survey to investigate the above discrepancy by providing an independent calibration for both surveys. This overlap region is essentially defined as 21°50 < α < 3°40 and −0.25° ≤ δ < 0.25°. We obtained images with the 2.5-m Isaac Newton Telescope (INT) and 1.0-m Jacobus Kaper Telescope (JKT) in 1994 October. The decision to use two telescopes was motivated by the number of close groups of Zwicky galaxies in the region, so that we use the 10-arcmin field of view available at the INT to image cluster fields containing groups of bright galaxies and the 6-arcmin field of view of the JKT to image individual galaxies. We used identical Tektronix 1024 × 1024 detectors (TEK3 and TEK4) and Harris B and R filters on the two telescopes. We obtained observations of 58 fields in two nights at the INT and 73 fields in three nights at the JKT with exposure times of 360 s and 600 s, respectively. We observed a number of photometric standards from the list of Landolt (1992), at hourly intervals throughout each night, as well as the field of the Active Galaxy AKN 120, which contains a number of photometric standards (Hamuy & Maza 1989).

The data were reduced using standard techniques as implemented in the IRAF CCDRED packages, with the exception that we used a modified version of the overscan correction routine to compensate for a saturation of the preamplifier used with TEK4 on the JKT. This effect manifested itself as a sudden drop in the overscan level following readout of particularly bright stellar objects in the field, and subsequent exponential recovery to the normal level as the next ~100 rows were read out. We found that this problem could be corrected by fitting the overscan regions on either side of the drop for those fields where the effect occurred. Extinction coefficients were derived each night, giving values in the range 0.10 ≤ k_B ≤ 0.12. We determined zero-points for the two combinations of telescope and detector to be

B_0,INT = 24.16 ± 0.02,  
and

B_0,JKT = 21.77 ± 0.02.  

We also obtained R-band images of our standards and target fields, with zero-points determined to be R_0,INT = 24.33 ± 0.1 and R_0,JKT = 22.11 ± 0.02, but we were unable to determine any significant colour term from our standard stars, consistent with previous experience with this combination of CCD and filters, which are designed to be very close to the Johnson–Cousins system.

3.2 Image detection and photometry

We used the Starlink psa image detection and photometry software for our photometric analysis. This is essentially the same...
as the image detection software used in the construction of the APM Galaxy Survey (Irwin 1986). The basic input parameters for the detection are the threshold intensity per pixel or surface brightness, \(I_s\), and the minimum size of the object to be detected, \(A_s\). Amongst other parameters \texttt{pisa} returns total area \(A_T\), the ellipticities and the isophotal magnitude \(B_I\) or the corresponding total magnitude \(B\) resulting from a curve of growth analysis for each detected object after removal of any overlapping objects.

Given that our CCD survey was designed to provide a calibration of both the APM and Zwicky data, we were necessarily interested in a wide range of magnitudes \(14 \leq B \leq 20\)† and image sizes. For this range of objects there was no unique combination of \(I_s\) and \(A_s\) that could deblend the faint objects without breaking the bright ones. In order to automate this process as much as possible for the whole range of magnitudes, we ran \texttt{pisa} several times with different combinations of \(I_s/A_s\). These are listed in Table 2.

|     | \(I_s\) (mag arcsec\(^{-2}\)) | \(A_s\) (arcsec\(^2\)) |
|-----|-------------------------------|------------------------|
| INT1| 26.1                          | 96                     |
| INT2| 25.7                          | 34                     |
| INT3| 25.4                          | 34                     |
| INT4| 25.0                          | 17                     |
| INT5| 24.6                          | 10                     |
| INT6| 24.4                          | 10                     |
| JKT1| 25.0                          | 12                     |
| JKT2| 24.5                          | 12                     |
| JKT3| 24.1                          | 6                      |
| JKT4| 23.7                          | 6                      |
| JKT5| 22.9                          | 3                      |

We chose a larger (smaller) area for the fainter (brighter) isophotes so as to select similar objects in all runs. Objects in the final catalogue were selected from the INT4 and JKT4 runs. The information from different isophotes was then used to perform an automatic rejection of broken or contaminated images. After rejection, the total magnitude and size were the largest remaining estimates of \(B\) and \(A_T\), which typically correspond to the faintest isophote left. The error in \(B\) was taken to be the variance in the different estimates for total magnitudes. Objects with rejected isophotes were automatically labelled and checked visually. We refer to total magnitudes estimated in this way as \(B_{\text{INT}}\) and \(B_{\text{JKT}}\) for the INT and JKT sets, respectively, or \(B_{\text{CCD}}\) in general. These effectively correspond to total magnitudes detected at isophotes 26.1 mag arcsec\(^{-2}\) and 25.0 mag arcsec\(^{-2}\), respectively, unless stated otherwise.

To check if our isophotes are low enough we have also computed total magnitudes determined by \texttt{pisa} using higher isophotes. We find a small zero-point shift of the total \(B_{\text{INT}}\) scale as a function of the isophote \(I\), but for a given \(I\) this shift is not a function of \(B\) over the wide magnitude range considered here. This is illustrated in Fig. 3, which shows a change of \(\approx0.2\) mag in the mean \(B_{\text{INT}}(I)\) when we change the isophote from \(I = 26.1\) to 24.0 mag arcsec\(^{-2}\). Changing the isophote from \(I = 26.1\) to 25.0 mag arcsec\(^{-2}\) introduces a change of only 0.1 mag. Changing the detection isophote from \(I = 26.1\) to 24.4 mag arcsec\(^{-2}\) also introduces a change in \(B_{\text{INT}}\) of about 0.2 mag. We therefore conclude that the residuals associated with our final choice of detection isophote are small compared to the shifts illustrated in Fig. 2.

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This analysis also implies that there should be a mean zero-point shift in the JKT data relative to the INT data of 0.1 mag due to the difference in the isophotes used. We therefore apply this shift to all objects observed with the JKT to transform these data to our \(B_{26.1}\) system.

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**Table 2.** Input parameter sets used for image analysis.

| Parameter | Value 1 | Value 2 |
|-----------|---------|---------|
| \(I_s\)   | 26.1    | 25.7    |
| \(A_s\)   | 96      | 34      |
| \(I_s\)   | 25.4    | 25.0    |
| \(A_s\)   | 34      | 17      |
| \(I_s\)   | 24.6    | 24.4    |
| \(A_s\)   | 10      | 10      |
| \(I_s\)   | 25.0    | 24.5    |
| \(A_s\)   | 12      | 12      |
| \(I_s\)   | 24.1    | 27.3    |
| \(A_s\)   | 6       | 6       |
| \(I_s\)   | 22.9    | 22.9    |
| \(A_s\)   | 3       | 3       |

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**Figure 3.** Comparison of total magnitudes \(B_{\text{INT}}\) for different isophotes: \(I = 26.1\) to 24.0 mag arcsec\(^{-2}\).

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**Figure 4.** The top panel shows the red magnitudes \(R_{\text{CCD}}\) for a subsample of INT galaxies as a function of the blue \(B_{\text{CCD}}\) ones. The bottom panel shows the colour \(B_{\text{CCD}} - R_{\text{CCD}}\) evolution as a function of \(B_{\text{CCD}}\).
Finally, we investigated the possibility that there could be a small effect due to the change in mean redshift of the samples at fainter magnitudes by searching for a change in the mean galaxy colour. Fig. 4 shows $B_{\text{INT}} - R_{\text{INT}}$† as a function of $B_{\text{INT}}$. There is only a small colour evolution within the errors. A linear fit to the binned data in Fig. 4 yields $B - R = 0.016B + 1.23$ with a mean $B - R = 1.50$ (the mean weighted by each galaxy is $B - R = 1.61$ and is dominated by the faint objects).

4 COMPARISON WITH THE ZWICKY CATALOGUE

In Fig. 5 we show the histograms of number counts for the 204 Zwicky galaxies in our sample to the different magnitude systems: Zwicky (top), APM (middle) and CCD (bottom). Comparison of the APM and CCD data here suggests that the effect shown in Fig. 2 is unlikely to be an artefact of saturation effects in the equatorial APM Survey data at bright magnitudes (see Section 2).

We searched for possible correlations between the magnitude differences, $B_{\text{CCD}} - m_Z$, and other properties of our sample. The top panel of Fig. 6 shows the $B_{\text{CCD}} - m_Z$ difference as a function of CCD colour $B - R$. The colour of Zwicky galaxies is similar to the mean colour in Fig. 4, $B - R = 1.5$, and there is no apparent correlation with $B_{\text{CCD}} - m_Z$ within the scatter. This is a useful check, as any large differences that were due to processing errors might be expected to show up as objects of extreme colour. The bottom panel of Fig. 6 shows the scatter in $B_{\text{CCD}} - m_Z$ as a function of right ascension (RA). Objects were observed in order of increasing RA on each night of our observing run, and so we would expect temporal drifts to show up as a correlation with RA. Again, there is no evidence of any trend. We also investigated possible variations with Galactic latitude (not shown here), and again found no evidence for trends in our data.

The top panel of Fig. 7 shows the $B - m_Z$ error as a function of the mean surface brightness for all Zwicky galaxies. Surface brightness is defined here as the ratio of isophotal magnitudes to the area above a threshold of $25.0\,\text{mag arcsec}^{-2}$ in the INT (triangles) and with a threshold of $24.1\,\text{mag arcsec}^{-2}$ in the JKT (circles). The difference in the threshold explains the systematic shift in the bulk value of mean high surface brightness of the JKT images (as we are closer to the galaxy core). As can be seen, there is no apparent variation of magnitude error with surface brightness.

The bottom panel of Fig. 7 shows the $B - m_Z$ error as a function of the sequential run number. This is close to observational time for the INT (triangles) or JKT (circles) when considered separately (in practice, some of the INT and JKT observations were made on the same night). There is no apparent variation of magnitude error with run number.

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Fig. 8 is the main result of this paper. It shows the Zwicky magnitude error $B_{\text{CCD}} - m_Z$ as a function of $B_{\text{CCD}}$. The dotted line corresponds to a direct least-squares fit to the data. The continuous line shows the fit corrected for Malmquist bias (see text).

This fit is the result of the interplay between the scatter in the two magnitude systems and the Zwicky survey limit (shown as dotted line in Fig. 8). As a result of this scatter, objects with faint $B_{\text{CCD}}$ and bright $m_Z$ can be included in the survey, but there is a deficit of objects with faint $m_Z$ and bright $B_{\text{CCD}}$, i.e. the fit suffers from a Malmquist type of bias. However, for a linear relation, it is apparent that Malmquist bias is insufficient to account for all of the effect shown in Fig. 8. We next develop a scheme to correct this fit for the effects of Malmquist bias.

4.1 Malmquist bias correction

Different magnitude systems are subject to different systematic errors and, even in the best of situations, intrinsic differences in the morphology, environment and spectrum of the galaxies tend to introduce stochastic fluctuations in any magnitude system. We want to find a best-fitting linear relation between the Zwicky, $m_Z$, and CCD, $B_{\text{CCD}}$, systems:

$$m_Z = \lambda B_{\text{CCD}} + Z,$$

(7)

where $\lambda$ will account for any scale difference and $Z$ is a zero-point shift. In general, both $m_Z$ and $B_{\text{CCD}}$ are stochastic variables and equation (7) is just a mean relation. As is common practice we will assume that there is Gaussian scatter around the above mean relation (resulting from the accumulation of multiple uncorrelated factors). That is, given a measured magnitude $m_Z$, the error is given by:

$$P(\Delta) = \frac{1}{N} \exp \left( -\frac{\Delta^2}{2\sigma^2} \right),$$

(8)

where $\Delta = m_Z - \bar{m}_Z$ is a stochastic variate, $\bar{m}_Z$ is some mean best-fitting value in the linear relation of equation (7), $\sigma$ is the rms error and $N$ is a normalization factor. For a sample that is not magnitude-limited we have $N = \sqrt{2\pi\sigma}$. For a magnitude-limited sample, where $m_Z < m_Z^{\text{lim}}$, the probability is the same but has a different normalization:

$$N = \int_{m_Z^{\text{lim}}}^{\infty} dm_Z \exp \left( -\frac{\Delta^2}{2\sigma^2} \right).$$

(9)

because not all magnitudes are possible, so that $\Delta = m_Z - \bar{m}_Z < m_Z^{\text{lim}} - \bar{m}_Z$. Thus, we can write $P(m_Z)$ in terms of the complementary error function (erfc):

$$P(\Delta) = \frac{2 \exp[-\Delta^2/(2\sigma^2)]}{\sqrt{2\pi\sigma} \text{erfc} \left[ (m_Z - m_Z^{\text{lim}}) / (\sqrt{2}\sigma) \right]}$$

(10)

so that for $m_Z^{\text{lim}} = \infty$ we recover the standard Gaussian result.

We are now able to perform a likelihood analysis to find the best-fitting values of $\lambda$ and $Z$ in the linear relation of equation (7). We define a likelihood as:

$$\mathcal{L} = \prod_i P(\Delta_i)$$

(11)

where $i$ runs over all galaxies in the survey, and:

$$\Delta_i = m_Z^i - (\lambda B_{\text{CCD}}^i + Z)$$

(12)

with $m_Z^i$ and $B_{\text{CCD}}^i$ the measured Zwicky and CCD magnitudes for galaxy $i$. In analogy with the standard $\chi^2$ test we define a Malmquist bias ‘corrected chi-square’:

$$\chi^2_{\text{Malm}} = \sum_i \left( \frac{\Delta_i^2}{2\sigma^2} + 2 \log \left[ \text{erfc} \left( \frac{\lambda B_{\text{CCD}}^i + Z - m_Z^{\text{lim}}}{\sqrt{2}\sigma} \right) \right] \right).$$

(13)

Note that the measured magnitude errors, $\sigma_i$, are added in quadrature to the stochastic error in the linear relation, $\sigma$, which is one of the parameters we want to determine with this fit.

The best-fitting values that we find on maximizing the likelihood, using the data in Fig. 8, are:

$$\lambda = 0.62 \pm 0.05,$$

$$Z = 5.9 \pm 0.7,$$

$$\sigma = 0.40 \pm 0.05.$$  

The errors correspond to approximate 99 per cent confidence levels. The values in each uncertainty range are strongly correlated: lower values of $\lambda$ (e.g. larger scale errors) are (linearly) correlated with larger values of $Z$, and both are obtained for the smaller $\sigma$. The inverse relation gives:

$$B_{\text{CCD}} = 1.61 m_Z - 9.5.$$  

(15)

Fig. 8 shows as a continuous line the best-fitting model for the corresponding best-fitting magnitude difference:

$$B_{\text{CCD}} - m_Z = (0.38 \pm 0.02)(B_{\text{CCD}} - 15.53) \pm 0.4.$$  

(16)
the autocorrelation for magnitude differences in magnitude scale. The zero-point different above analysis indicates both a zero-point shift and a change of a Gaussian with the same dispersion, $s$. 

Thus, after correcting for the effects of Malmquist bias, the above analysis indicates both a zero-point shift and a change of scale error by estimating the magnitude correlations as a function of projected separation. Fig. 10 shows the mean correlation $\langle \Delta \theta_{ij} \Delta \theta_{ij} \rangle$ as a function of the pair separation $|\theta_i - \theta_j|$, in arcmin. The uppermost panel shows the autocorrelation for magnitude differences in the Zwicky system, $\Delta Z^2 = m^2_Z - \langle m_Z \rangle$, where $m_Z$ is the Zwicky magnitude for the $i$th galaxy and $\langle m_Z \rangle$ is the mean Zwicky magnitude in the survey. The middle panel shows the corresponding autocorrelation for the CCD system: $\Delta CCD = B^2_{CCD} - B_{CCD}$. The lower panel shows the zero values for reference. The short-dashed line in the lower panel shows the prediction based on applying equation (18) to the data, which is extremely close to the observed result.

We can see in Fig. 10 that there is a significant angular correlation between nearby magnitudes and positions with $\theta \leq 1$ arcmin. This correlation is followed by the errors, indicating that the above model is valid. The Zwicky system shows smaller correlations and smaller variance than the CCD system. This can also be understood in the context of the model, as in the Zwicky system the ‘effective’ magnitude scale is about a factor of 2 smaller than the CCD range.

Note that at the typical depth of the survey, $D = 80$ Mpc, the above magnitude correlations are only significant at physical scales smaller than $\leq 100 h^{-1}$ kpc. This correlation has little effect on typical galaxy clustering scales, $r_0 = 5$ Mpc, but might be relevant for the inversion of angular clustering on smaller scales. For example, Szapudi & Gaztañaga (1998) find that on scales $\theta \leq 0.1$ arcmin there is a significant disagreement between the APM and the Edinburgh/Durham Southern Galaxy Catalogue (EDSGC) that is attributed to differences in the construction of the surveys, most likely the dissimilar deblending of crowded fields. At the depth of these surveys, $D = 400$ Mpc, the above magnitude correlations correspond to $\theta \leq 1$ arcmin and could also have a significant effect on the angular clustering and its interpretation on these small scales.

4.2 An illustration

An illustration of the scale error in the Zwicky system can be seen in the galaxies shown in Figs 11 and 12. Table 3 gives the Zwicky and CCD magnitudes for each of the Zwicky galaxies as labelled in the figures. As can be seen from the table, the range of Zwicky galaxies in Fig. 11 is $\Delta m_Z = 0.3$, which is almost 6 times smaller than the CCD range $\Delta B_{CCD} = 1.7$. The range for the whole cluster is $\Delta m_Z = 1.3$, almost a factor of 3 smaller that the CCD range: $\Delta B_{CCD} = 3.5$. These illustrations are strongly suggestive of an observer-bias effect, whereby some fainter galaxies are included as a result of their proximity to brighter objects, e.g. object number 9 in Fig.12.
We will now present some further properties of the galaxies in our sample: colours, sizes and ellipticities, and discuss the implications for the luminosity function. This will help us to understand the systematic effects present in the Zwicky magnitude system. As mentioned in Section 1, these local properties are interesting in the context of galaxy evolution and star formation rates.

There are still only few samples that are both homogeneous and large enough to provide estimates of the statistical properties of nearby samples, most of which have been selected from photographic plates. Besides the redshift catalogues listed in Table 1, one of the more extensive catalogues of bright galaxies is contained in the ‘Second Reference Catalogue of Bright Galaxies’ (de Vaucouleurs, de Vaucouleurs & Corwin 1976, known as RC2), which gives magnitudes, colours, ellipticity and morphology for well over a thousand galaxies to a limiting isophote of around $25.0 \, \text{mag arcsec}^{-2}$. The problem with this catalogue is that it is a mere compilation of data and was not intended to be complete to any specified limiting magnitude, diameter, or redshift. Moreover, it is based on photographic plates.

Our sample is homogeneous enough and extends over a large enough area ($\approx 400 \, \text{deg}^2$) to provide a fair sample. Thus the new results based on the CCD magnitudes should be a good local reference for the fainter studies of galaxy evolution.

We will compare the properties of galaxies in the Zwicky ($m_Z < 15.5$) sample with the corresponding properties of galaxies in the INT fields selected using the CCD blue magnitude $B = B_{\text{CCD}}$. We choose two magnitude cuts: $B < 16$, which includes most Zwicky galaxies, and $19 < B < 20$, which includes faint galaxies in the same fields.

### 5.1 Sizes and ellipticities

Fig. 13 shows a histogram of the frequency distribution of galaxies as a function of its area (number of galaxy pixels above detection threshold in the CCD image). The top panel shows Zwicky selected galaxies only. The middle and bottom panels include all the galaxies in the INT fields selected with CCD magnitudes of $B < 16$ and $19 < B < 20$, respectively.

As can be seen in the figure, Zwicky selected galaxies have a long tail of small objects, which is not present in the bright subsample of $B < 16$ CCD selected objects. This again illustrates the scale error (and selection biases) in the Zwicky system mentioned above (see also Section 6).

The distributions of sizes in logarithmic scale for both CCD subsamples are well approximated by Gaussians (shown as continuous lines in the figure). The mean size is about $60 \, \text{arcsec}^2$ for $19 < B < 20$ and $1600 \, \text{arcsec}^2$ for $B > 16$, with an rms dispersion of about 20 and 27 per cent respectively (recall that these areas correspond to a nominal threshold of $26.1 \, \text{mag arcsec}^{-2}$; fainter thresholds could be needed to sample the size of the lower surface haloes).

Fig. 14 shows the corresponding frequency distribution for the ellipticities as measured in the galaxy shapes (with a threshold of $26.1 \, \text{mag arcsec}^{-2}$). These figures are in rough agreement with the...
results by Binney & de Vaucouleurs (1981) over the Second Reference Catalogue (RC2).

The local distribution seems remarkably similar to the faint one, given the large differences in sizes shown in Fig. 13. This is a good indication that our isophote (26.1 mag arcsec$^{-2}$) is low enough, as otherwise we would expect a large excess of round faint objects. There seems to be nevertheless a slight ($\approx 5$ per cent) excess of round faint objects. This is probably not the result of the seeing (or pixel resolution) as most of the faint objects here have more than 30 arcsec$^2$ (or 100 pixels) of area (see Fig. 13). The lack of correlation between ellipticities $e$ and areas $A$ is illustrated in the bottom panel of Fig. 13. A least-squares fit to the points gave $e = 0.277 + 0.018 \log_{10}(A)$.

### 5.2 Colours

Both the morphology and a more detailed study of colours will be presented elsewhere. Here we just show the colour frequencies and discuss some of the implications.

Fig. 15 shows the frequency distribution of CCD colour $B - R$ for Zwicky galaxies selected in different ways: (a) all Zwicky in our sample (top), (b) Zwicky galaxies in our JKT subsample (middle) and (c) Zwicky galaxies in our INT subsample (bottom). The same Gaussian distribution is plotted as a solid line in each panel.
Given the large area covered (several hundreds of square degrees), these results should be a good estimate of the overall mean colour of bright local galaxies. How do these values compare with previous studies? This is a difficult question because it requires both accurate colours and the adequate fraction of galaxies in different environments (e.g. different morphological types). Previous studies were limited to inhomogeneous samples (e.g. RC2) or to small numbers of galaxies. For example, Kennicutt (1992) presented results for eight early-type galaxies (e.g. RC2) or to small numbers of galaxies. For example, Kennicutt (1992) presented results for eight early-type galaxies and 17 spirals to irregulars. Our mean $B - R = 1.47$ can be compared against the synthetic $B - R$ colours presented by Fukugita, Shimasaku & Ichikawa (1995). We have used Harris filters, which were designed to be very close to the Johnson–Cousins (with $R$ Johnson) system. In these broad bands, table 3 of Fukugita et al. shows $B - R = 1.67$ for ellipticals, 1.48 for S0, 1.2–1.1 for spirals and 0.6 for irregulars. The range seems in rough agreement with Fig. 15, although we find a significant number of objects with $B - R > 2$. Notice that these objects are mostly in the INT sample, i.e. in clusters or groups, while most of the bluer objects with $B - R < 1$ are in the JKT fields, i.e. they are more isolated (by angular separations larger than 6 arcmin, which corresponds to a mean separation larger than $140 h^{-1}$ kpc). Nevertheless, this seems to be a small effect.

Note that the Fukugita et al. synthetic colours seem to be slightly less red than the Kennicutt (1992) observations (according to table 2 in Fukugita et al., they are about 0.1 redder in $B - V$ and this could be larger in $B - R$). Also notice that we are using total magnitudes, while the synthetic colours are based on small-aperture spectra. Galaxies could have quite a different colour distribution (or spectra) in their low-surface haloes.

Fig. 16 shows the frequency distribution of CCD colour ($B - R$) for the Zwicky galaxies (top panel) in comparison with the same galaxies selected with CCD magnitudes: with $B < 16$ (middle panel) and a subset of INT galaxies with $19 < B < 20$ (bottom panel), which corresponds to the points in Fig. 4. The continuous line in all cases shows for reference a Gaussian distribution with mean $B - R = 1.45$ and rms deviation of $\sigma = 0.4$, which roughly matches the Zwicky frequencies.

It is interesting to notice the peak of local galaxies with $B - R = 1.5$ and the spread and shift to the red of the faint objects in the bottom panel. These magnitudes are not $k$-corrected, which could well explain the relative reddening of the faint objects.

5.3 The local CfA2 luminosity function

Zwicky magnitudes have been used to estimate the LF in the CfA2 redshift catalogue (Marzke et al. 1994). Marzke et al. used a Monte Carlo method to estimate how the LF parameters would change if the dispersion $\sigma_S$ were 0.65 mag (closer to what we find here than the nominal 0.3 mag they used). They found that the true $M_s$ should be about 0.6 mag brighter, and that a similar conclusion would be reached for a small scale error. Marzke et al. used this estimate to conclude that a combination of incompleteness and a small (0.2 mag) scale error would be sufficient to move the CfA2-north values to those found from CfA2-south.

A detailed analysis of the implications of our new Zwicky magnitude calibration on the LF would require the redshift information, and this is left for future work. It is nevertheless possible to use the mean relation that we found to show how we expect the LF to change.

In practice, when fitting the Schechter parameters in equation (1) to observational data, the value of $\phi_\ast$ is correlated with the values of $M_s$ and $\alpha$. In our case we do not use a fit to data, but just model how the LF changes with a homogeneous linear shift in the magnitude scale. A zero-point shift $Z_0$ in the magnitude scale, as in equation (17), will just change the value of $M_s$:

$$M_s(\text{corrected}) = M_s + Z_0. \tag{19}$$

As the LF measures the number density of galaxies per magnitude interval, a linear change in the magnitude scale will shift the amplitude of the LF proportionally to the shift in the magnitude interval, i.e. by $\lambda$ in equation (18). Thus we have:

$$\phi_\ast(\text{corrected}) = \lambda \phi_\ast. \tag{20}$$

Thus the scale and zero-point error in the Zwicky system give the following corrections for the CfA2-south results of Marzke et al. (1994):

$$\phi_\ast(\text{corrected}) = \lambda \phi_\ast = 0.0124 \pm 0.006 h^3 \text{ Mpc}^{-3} \tag{21}$$

$$M_s(\text{corrected}) = M_s + Z_0 = -19.3 \pm 0.3. \tag{22}$$

If applied to the LF for the whole CfA2 survey:

$$\phi_\ast(\text{corrected}) = \lambda \phi_\ast = 0.025 \pm 0.009 h^3 \text{ Mpc}^{-3} \tag{23}$$

$$M_s(\text{corrected}) = M_s + Z_0 = -19.1 \pm 0.2, \tag{24}$$

where we have added the errors in quadrature. Thus the corrected values are now closer to the SAPM and LCRS (see Table 1). This can also be seen in Fig. 17, where we compare the corrected CF2 luminosity function given above with the one corresponding to the SAPM. Note that the latter is in the APM $b_0$ band, so that there could be some additional zero-point shifts between them (see Section 2).
6 CONCLUSION

In this paper we have presented CCD magnitudes for galaxies around 204 Zwicky galaxies which sample over 400 deg$^2$, extending 6h in right ascension. This subsample is drawn entirely from volume V of the Zwicky catalogue. We find evidence for a significant scale error as pointed out by Bothun & Schommer (1982) and Giovannelli & Haynes (1984). This is found by direct likelihood analysis, corrected for Malmquist bias, and also by noticing the angular correlations between the errors (Fig. 10) or the long tail of small objects in the frequency distributions of sizes (Fig. 13). The mean scale magnitude error is quite large: $\Delta m_z = 0.62 \Delta b_{\text{CCD}}$, i.e. an error of 0.38 mag mag$^{-1}$, while the mean zero-point is about $-0.35$ (equation 17), in agreement with Efstathiou et al. (1988).

An illustration of the scale error in the Zwicky system can be seen in the galaxies shown in Figs 11 and 12. These illustrations are strongly suggestive of an observer-bias effect, whereby some fainter galaxies are included in the sample because of their proximity to brighter objects, e.g. object number 9 in Fig. 12. This bias can also be seen in statistical terms as a long tail of small objects in the frequency distribution of Fig. 13.

Huchra (1976) found only a 0.08 mag mag$^{-1}$ scale error in a calibration of Zwicky galaxies with photoelectric photometry of a sample of 181 Markarian galaxies, which are preferentially spirals. As spiral galaxies are bad tracers of clusters or groups, it is unlikely that these Markarian galaxies include any of the fainter galaxies that contribute to the proximity observer bias mentioned above (which are mostly ellipticals). This effect would be hard to notice with photoelectric photometry, which samples only one object at a time. Note that our analysis is restricted to a narrow range of magnitudes $13.5 < m_Z < 15.5$, as compared to the wider range in Huchra (1976), but this narrow range contains the majority of the galaxies with $m_Z < 15.5$ and therefore dominates all the relevant statistical properties (such as the luminosity function).

Bothun & Cornell (1990) have studied the calibration of the Zwicky magnitude scale using a sample of 107 spiral galaxies. They suggest that the errors in $m_Z$ are minimized if $m_Z$ is an isophotal magnitude at $B = 26.0$ mag arcsec$^{-2}$, although it is clear from their Fig. 2 that even within such a small sample of objects there is a 5 mag range of isophotes that give isophotal magnitudes corresponding to $m_Z$. This suggests that our isophotal detection limit should be optimal for this comparison.

Takamiya, Kron & Kron (1995), also with photoelectric photometry, find evidence for a large scale shift between volume I and volumes II and V of the Zwicky catalogue. This shift appears to be of order 0.5 mag mag$^{-1}$ over the range $14 < m_Z < 15.7$, which is comparable to our findings for volume V, although they find very little effect for volumes II and V. However, we note that Fig. 4 of Takamiya et al. shows $B - m_Z$ versus $M_Z$, rather than $B$. A similar representation of Fig. 8 of this paper looks very similar to fig. 4(a) of Takamiya et al., which is reasonable, given that Fig. 8 implies a strong compression of the $m_Z$ axis, which effectively hides the scale error. Unfortunately, the overlap between the 204 objects in our sample and the 155 objects in the Takamiya et al. data is too small to draw any detailed comparison, given that there are ~600 Zwicky galaxies within the region of our survey.

We have also estimated how this scale error could change the CfA2 luminosity function in Section 5.3. Fig. 17 shows how the corrected estimation is now closer to other local estimates, such as the SAPM. Finally, in Section 5 we give properties of the galaxies in our sample: colours, sizes and ellipticities, providing one of the largest samples of this kind. The local colour frequency distribution can be well approximated by a Gaussian distribution with mean $B - R = 1.45$ and rms deviation of $\sigma = 0.40$. These colours compare well with synthetic $B - R$ colours presented in Fukugita et al. (1995). But there is a significant number of galaxies with $B - R > 2$ which are preferably found in clusters and groups, while most of the bluer objects with $B - R < 1$ (spirals to irregulars) seem more isolated. These local properties are interesting in the context of galaxy evolution and star formation rates. This will be studied in more detail in future work.
ACKNOWLEDGMENTS

The Isaac Newton Telescope (INT) and Jacobus Kapteyn Telescope (JKT) are operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. We thank Steve Maddox, Will Sutherland, John Loveday, Cedric Lacey, Michael Vogeley and Gary Wegner for useful discussions. We also thank the referee for helpful and constructive comments. This work has been supported in part by CSIC, DGICYT (Spain), projects PB93-0035 and PB96-0925, in part by PPARC (UK), and by a bilateral collaboration (Accion Integrada HB1996-0091) between CSIC (Spain) and the British Council (UK). Part of the data reduction and analysis was carried out at the University of Oxford, using facilities provided by the UK Starlink project, funded by PPARC.

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