Segregated Optical–NIR colour distributions of MDS galaxies

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ABSTRACT

We present a $K$ survey of 29 fields covering approximately 90 arcmin$^2$ from the Medium Deep Survey (MDS) catalogue down to a completeness magnitude of $K = 18.0$ (limiting magnitude $K = 19.0$). The morphology obtained by the MDS team using high resolution images from HST/WFPC2 along with our NIR observations allow a Colour–Magnitude and Colour–Colour analysis that agrees in general with spectral evolution models \citep{BruzualCharlot1998} especially if a reasonable range of metallicities for the Simple Stellar Populations used ($0.2 < Z/Z_\odot < 2.5$) is considered. However, a significant population of spheroids was found, which appear bluer than expected, confirming previous observations \citep{Forbes1996, Koo1996, Glazebrook1998}. This blueness might possibly signal the existence of non-negligible star formation in ellipticals and bulges at medium redshift. A number counts calculation for different morphological types show disks become the dominant population at faint magnitudes. The median redshift of the sample is $z \sim 0.2$, from a photometric redshift estimation using $V-K$ and $I-K$. A search for EROs in the survey field was also performed, with no detection of objects having $I-K > 4.5$, setting an upper limit to the number density of EROs at $dn_{\mathrm{ERO}}/d\Omega < 0.011\,\mathrm{arcmin}^{-2}$ ($K \leq 18.0$).

Key words: cosmology: observations – surveys – galaxies: evolution – infrared: galaxies

1 INTRODUCTION

With the advent of the Hubble Space Telescope, observational cosmology has been capable of extending the study of galaxy formation and evolution to epochs corresponding to less than one third of the age of the Universe. The extremely narrow PSF produced by HST/WFPC2 images (around 0.1 arcsec) allow morphological classifications of galaxies at medium to high redshifts. The Medium Deep Survey key project \citep{Griffiths1994} has been classifying field galaxies from hundreds of WFPC2 images, providing photometry in two bands (F606W and F814W, which roughly correspond to standard $V$ and $I$, respectively) as well as morphology down to $I \sim 22.0$. These data allow the study of number counts selected by type in $I$ and $V$ bands \citep{Griffiths1994, Driver1995, Abraham1996}. The results indicate that counts in elliptical and spiral galaxies match closely the predictions of non-evolving models, whereas the population of irregular/peculiar galaxies presents an excess over no-evolution estimations. The median redshift for spectroscopically confirmed galaxies is $z = 0.5$.

Inside knowledge of formation and evolution processes conforming the observed field galaxy population mixture requires additional data. Spectroscopic studies will provide intrinsic luminosities as well as information about absorption and emission lines. Besides, optical–infrared colours are sensitive to the stellar population content. Optical emission comes mostly from young OB stars while the old stellar population dominates the infrared luminosity. In a recent paper, Glazebrook et al. (1998) study the characteristics of the faint MDS population through optical spectroscopy and near-infrared photometry. An excess of blue ellipticals is found in $I-K$ distributions compared to pure luminosity evolution models. The main purpose of this work is to study the characteristics of normal galaxies in MDS fields through optical-infrared colours.

This paper is organized as follows: A detailed account of the observations and data reduction processes is presented in Section 2. We present the number counts in $K'$ band, compare them with previous observations and discuss the morphologies contributing at different magnitudes, in Section 3. Sections 4 and 5 are dedicated to optical–infrared
Table 1. MDS/MAGIC survey fields

| Field   | R.A.(J2000.0) | Dec.(J2000.0) |
|---------|---------------|---------------|
| uqk00  | 07 42 44.0   | +65 06 08.0  |
| usp00  | 08 54 16.0   | +20 03 41.0  |
| uzp00  | 11 50 29.0   | +28 28 53.0  |
| uzx03  | 12 10 34.0   | +12 19 05.0  |
| uzx01  | 12 30 54.0   | +12 19 05.0  |
| u26x1  | 14 15 20.0   | +52 03 01.0  |
| u26x2  | 14 15 14.0   | +52 01 50.0  |
| u26x3  | 14 15 07.0   | +52 00 40.0  |
| u26x9  | 14 17 23.0   | +52 25 13.0  |
| u26xa  | 14 17 17.0   | +28 24 03.0  |
| u26xb  | 14 17 10.0   | +52 22 53.0  |
| u26xc  | 14 17 04.0   | +52 21 43.0  |
| u26xd  | 14 16 57.0   | +52 20 33.0  |
| u26xe  | 14 16 51.0   | +52 19 13.0  |
| u26xf  | 14 16 44.0   | +52 18 13.0  |
| u26xg  | 14 16 38.0   | +52 17 53.0  |
| u26xh  | 14 16 31.0   | +52 17 53.0  |
| u26xi  | 14 16 25.0   | +52 16 43.0  |
| u26xj  | 14 16 18.0   | +52 15 32.0  |
| u26xk  | 14 16 12.0   | +52 12 22.0  |
| u26xl  | 14 16 05.0   | +52 11 12.0  |
| u26xm  | 14 15 59.0   | +52 10 02.0  |
| u26xn  | 14 15 52.0   | +52 08 52.0  |
| u26xo  | 14 15 46.0   | +52 07 42.0  |
| u26xp  | 14 15 39.0   | +52 06 31.0  |
| u26xq  | 14 15 33.0   | +52 05 21.0  |
| u26xv  | 14 15 27.0   | +52 04 11.0  |
| u26xv  | 15 19 41.0   | +52 02 05.0  |

colour relations, the latter focusing on the blue spheroid population found. A search for Extremely Red Objects is shown next. Finally, a discussion of our results is presented in Section 7.

2 OBSERVATIONS & DATA REDUCTION

The targets for our $K'$-band survey were chosen from the Medium Deep Survey catalogue that can be accessed at the HST/MDS Archive [http://archive.stsci.edu/mds/mds.cgi]. Our search was based on optimal positioning in the sky for our observing time and place, taking extra care not to bias the catalogue towards regions nearby quasars, active galaxies or other peculiar objects. We found a set of images taken under HST program GTO5090 (E.Groth as Principal Investigator) out of which 22 fields were selected. $K'$-band images of the MDS fields were obtained at the 2.2m MPIA telescope on Calar Alto, Spain during the nights of 1997 February 18,20 and May 21, with MAGIC, a NIR camera that uses a NICMOS3 256$^2$ Rockwell HgCdTe array, with a pixel scale of 0.64 arcsec.

Five-second individual exposures were taken, adding up 12 of them into a single 1 minute file. Between frames we nodded the telescope in steps of 10 arcseconds, following a path that closed in 9 steps. Each field has three such sets totaling 27 minutes of integration time. Several UKIRT faint photometric standard stars were also imaged throughout each night. The fields were flatfielded using the median of the set of images for each field excluding that of the frame being processed. The complete sample comprises 29 fields (table 1) which covers a 116.8 arcmin$^2$ region in the $K$-band, with a 89.4 arcmin$^2$ overlap with the HST/WFPC2 images.

A translation from the HST/WFPC2 filters to standard $V$ and $I$ photometry is done using the transformation formulae from Holtzman et al. (1995) and approximating $V-I$ to $F606W-F814W$. The additional correction terms are less than 0.01 mag.

The object detection process was done using SExtractor [Bertin & Arnouts 1996] using a 2.5$\sigma/\sqrt{N}$ detection threshold. $N$ is the number of connected pixels within one seeing disc. Hence, the global threshold is 2.5$\sigma$. Even though this value might be rather low for individual band detection, we are only considering those objects that appear both in the $K$ and MDS-$I$ or $V$ images. We compared the aperture and isophote-fitting photometry from SExtractor and IRAF’s QPHOT task using 4, 5 and 6 arcsecond disks and found the maximum uncertainty to lie around 0.2 mag down to a limiting magnitude of $K = 19$. Eventually, we decided to use a 6 arcsec aperture photometry, which guarantees all of the flux from each object is measured. Moreover, this is the same aperture used by Glazebrook et al. (1998), which allows a better comparison.
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In order to match the WFPC2 and MAGIC images, we retrieved individual HST frames for each field from the STScI archive (with exposure times around 1,000 seconds) and compared them to our NIR images. We took several objects in each field to find the pixel-to-coordinate mapping. Many of the images used in the survey overlap, and so we checked for objects appearing twice. Table 2 shows the number of objects detected as well as the ratio of spheroids and disks in the sample (Bulge to Disk ratio > 0.75 and < 0.25 respectively). As expected, the bias in imposing detection in all bands: V,I and K implies a higher proportion of disks, compared to only imposing I and K detection.

The completeness magnitude was estimated in two different ways: A quick method involves searching for the peak in the histogram of objects appearing both in K and I bands to make sure we were rejecting spurious detections. This method is only possible as long as we are working with images that are much deeper in I than in K, so that no severe bias is included by enforcing I band detection. Besides, the peak of the histogram will only show the completeness level as long as the Luminosity Function is monotonically increasing in the detection range (which is our case; see, for instance, fig. 1). The second method consists of simulating a random field of pointlike galaxies with the Luminosity Function obtained from the literature (cf. fig 1) and with the same sky noise and pixel size. We could have considered a sample of spheroids and disks in the simulated sample as the threshold of detection deals with surface brightness; however, most of the galaxies from the MDS catalogue had half-light radii well below 1.5 arcsec (see, for instance, table 3) which was our resolution taking into account seeing conditions and pixel size. Both methods yielded a completeness magnitude of K = 18.0.

Table 2. Survey Properties

| Band     | Comp.Mag. | Objects | Spheroid(%) | Disk(%) |
|----------|-----------|---------|-------------|---------|
| F606W (V) | V < 21.8  | 276     | 9.8         | 62.7    |
| F814W (I) | I < 21.0  | 377     | 15.1        | 53.8    |
| I + K     | K < 18.0  | 170     | 18.0        | 40.0    |
| V + I + K | K < 18.0  | 109     | 14.0        | 45.0    |

3 NIR NUMBER COUNTS AND MORPHOLOGY

We construct the number counts in the NIR with the objects detected by SEExtractor in the MAGIC images which have counterparts in MDS I band frames. Even though this might appear as a severe bias on the sample, it is not, as can be seen in figure 1, where our I + K sample is shown along with data from the literature. A strong bias would appear as a paucity of objects and thus a disagreement with previous K band surveys. The only population that might drop out in this process would consist of blue irregular galaxies, which contribute negligibly to the Luminosity function in our magnitude range (K ≤ 18).

The counts follow a dlogN/dm relation with a slope of ~ 0.4 in the range 16 ≤ K ≤ 18. Differential number counts versus K magnitude of our sample are presented in figure 1 (solid triangles), along with Poissonian error bars. Just for comparison, a no-evolution model (solid line) based on the luminosity function given by Efstathiou et al. (1988) is also presented. We assume a cosmology with Ω0 = 0 and H0 = 50 km/sec/Mpc and a galaxy mixture (including SFRs and IMFs) as prescribed by Pozzetti, Bruzual and Zamorani (1996). The k-corrections and colours are calculated for different types of galaxies using the spectral synthesis code from Bruzual and Charlot (1998). The model has been normalized to the observations from the literature at 18 < K < 18.5 (the present sample not included). The no-evolution model is compatible with the observations down to our completeness magnitude. Moreover, the NIR number counts down to K ~ 20 cannot discriminate between no-evolution and passive luminosity evolution models (Pozzetti et al. 1996). On the other hand, the slope of the K band number counts seems to flatten for the faintest magnitudes (Djorgovski et al. 1995, Moustakas et al. 1997).

Unlike many previous K band surveys, now we have access to the morphology of the objects from the I and V band images classified by the MDS group. Figures 2 and 3 serve as a test of the contribution from each morphology to the counts in different bands. We plotted in figure 3 the fraction of the total number of galaxies detected in I and K (top) and in V, I and K (bottom) versus the bulge to total luminosity ratio measured in I. As in a typical field sample, the proportion of disk galaxies is higher than that of bulges. The percentage of the latter (B/T > 0.75) is smaller in the sample selected in V,I and K than in the one selected in I and K alone. This result follows the ratios observed in the MDS objects in the two filters I and V (see table 2). From figure 2 (top), one can notice that the ratio of bulges in field galaxies decreases as we go to fainter magnitudes, down to ~ 1/10 at K = 18.0, whereas the disk population...
Figure 3. Bulge-to-Total fractions in $I+K$ and $V+I+K$ selected samples (solid lines). The dashed lines represent the histogram without the constraint of $K$ band detection.

comprises roughly 60% of the sample at the faint end. The contribution of the different populations to the differential number counts at different $K$ magnitudes is presented in figure 2 (middle and bottom panels). One can see in both figures the trend indicated above: faint magnitude counts are clearly dominated by disks.

4 COLOUR–MAGNITUDE RELATIONS

Figures 4a and 4b show the colour–magnitude relation for our sample in $V−K$ and $I−K$. Having the morphology of each object, we can go further and predict the colours that galaxies with a given morphology should have. The shaded regions in these figures show the range of colours expected for galaxies with redshift $0 < z < 1$, according to the models of Bruzual & Charlot (1998) for two metallicities: one higher above solar ($2.5Z_\odot$) and another lower than solar ($Z_\odot/5$). All of them have a Scalo IMF defined for $0.1M_\odot < M < 100M_\odot$ and an exponential Star Formation Rate with a characteristic time $\tau$. The morphology determines the value of $\tau$: 1 Gyr for bulges, 5 Gyr for bulge + disk and $\infty$ (i.e. constant SFR) for disks. The formation redshift for all three models is $z_F = 5$. Given the degeneracy which exists between age and metallicity (e.g. Worthey 1994), we can account for a range of colours either by changing the formation redshift or by using different metallicities. In the figures we used the latter: we can see a lower metallicity shifts the colour blueward in the same way a lower formation redshift would.

Unfortunately, we do not know the redshifts of these galaxies and so we cannot compare the trajectory predicted by the models with the colours of MDS galaxies. One is tempted, though, to use a $K−z$ relation from deep surveys (Cowie et al. 1996); however the spread in this relation is too large to produce a meaningful result. A colour–colour plot avoids the estimation of redshift, and is shown in figure 5.

The dotted, solid and dashed lines correspond to three different metallicities, namely: $Z/Z_\odot=2.5,1.0$ and 0.2, respectively. The solar metallicity curve also gives the redshift as crosses, from $z = 0$ (blue-blue i.e. lower left corner) up to $z = 1$ in steps of $\Delta z = 0.1$. There is good agreement with the colour–colour trend for all three morphologies, although a range of metallicities (or of formation redshifts) is needed to account for quite a few of the galaxies. It is worth mentioning this issue as either age or metallicity can account for...
this range of colours. The few disks with a red $V - K$ and $I - K$ colours in figure 5 which fall away from the model predictions should be considered with care as they fall close to the detection limit in $V$ and $I$ and so the photometric error in these bands could be large. The result for spheroids is treated in the next section.

Finally, we left as an interesting exercise to compute the values estimated for the redshift using a purely photometric approach. This method compares the broadband colours with templates associated with the morphology of the galaxy, shifting the redshift until the predicted colours are compatible with the observations. The more bands used, the better estimation one should have. Photometric redshift measurements can be thought of as a “poor man’s spectroscopy”. Previous work on the subject has achieved remarkable accuracy: Brunner et al. (1997) did a multiband analysis which resulted in a dispersion $\Delta z \sim 0.02$ up to $z = 0.4$. A deeper estimation of the uncertainties can be found in Hogg et al. (1998).

In our case, we just have two colours ($V - K$ and $I - K$), which drove us to use a simple method to estimate the redshift, namely: minimize the squared difference between predicted and observed colours, using for each morphological type the models described above with three different metallicities. We imposed as a valid estimation that which corresponded with a colour difference less than $\pm 0.5$ mag, which reduced the sample to roughly 45 %. The histogram of the objects can be seen in figure 6, which has a median around $z \sim 0.2$. Even though the value for the complete MDS sample is 0.5, our lower redshift is reasonable as the NIR survey done in the present work is only complete down to $K = 18$.

5 BLUE SPHEROIDS IN THE FIELD

The right panels of figure 5 plot the spheroids in two different colour–colour diagrams. In both cases the observations fall blueward of the passive evolution estimations from spectral evolution models. This is proof of the existence of ongoing star formation. Besides, the mismatch is bigger in $V - K$, than in $I - K$, possibly a sign that there is more flux into $V$ — i.e. restframe $U$ and $B$ — accounted for by young stars. Although the environment is totally different, this blueness is in agreement with the colours of some cluster ellipticals (e.g. Couch & Sharples 1987) for which a recent episode of star formation must be considered in order to explain it (Charlot & Silk 1994). Confirmation of the existence of blue ellipticals in MDS fields appears in spectroscopic observations using the Keck telescope (Forbes et al. 1996, Koo et al. 1996). We inspected visually all the spheroids in our sample and found only one possible misclassified object which appears as a late-type galaxy. The list of all 15 spheroids with their properties appear in table 3. These blue early-type galaxies should be further studied as they might throw light on the galaxy formation process both in the field and in clusters.

6 SEARCHING FOR EROS

A search for Extremely Red Objects (EROs) was also undertaken on this sample. First of all we checked that none of the objects found both in the $K$ band images and the HST/MDS catalog from the $I$ band frames had a colour characteristic of such sources ($I - K > 4.5$). Next, we considered those objects from our $K$ band images alone, which did not appear in the MDS catalog and visually inspected both the NIR and the HST/MDS images (the latter retrieved through the archive of the STScI). About half of the candidates detected in $K$ fell in a region which did not overlap with the HST $I$ or $V$ images. The other half had counterparts which were either very bright stars or galaxies which failed to adjust to the predetermined luminosity profiles. In either case, these objects were brighter than $I \sim 21$ and so they had $I - K < 3$, i.e. bluer than the standard criterion for an Extremely Red Object ($I - K > 4.5$). Hence, all the objects detected in our $K$ band images — at a completeness level of $K = 18$ — had counterparts in $I$ and had colours $I - K < 4.5$. The sample extends over 89.4 arcmin$^2$, which sets an upper limit for the number density of EROs at $dn_{ERO}/d\Omega < 0.011$ arcmin$^{-2}$ (for $K \lesssim 18$).

7 DISCUSSION

In this paper we have performed NIR photometry in 29 fields from the Medium Deep Survey catalogue. The number counts obtained (figure 1) for objects detected both in $I$ and $K$ band frames agree well with previous $K$ band surveys. This agreement is possible since the $I$ band images are deeper. The morphology obtained with high resolution images from HST/WFPC2 allows a segregated study of colour-magnitude and colour-colour relations for three different types according to the bulge-to-disk ratios. As expected, spheroids appear redder in $V - K$ and $I - K$ than...
Table 3. Spheroids from MDS/MAGIC Survey

| ID | F814W | F606W−F814W | F814W−K | rHL(arcsec) | B/T | Field   |
|----|-------|-------------|---------|------------|-----|---------|
| E1 | 19.83 | 0.83        | 2.97    | 0.37       | 1.00| uqk00   |
| E2 | 19.75 | 1.80        | 3.70    | 0.52       | 0.82| uzk03   |
| E3 | 20.47 | 1.50        | 3.10    | 0.37       | 1.00| uzk03   |
| E4 | 19.42 | 1.46        | 3.03    | 0.49       | 0.76| u26x1   |
| E5 | 20.19 | 1.63        | 2.69    | 0.29       | 1.00| u26x1   |
| E6 | 19.75 | 1.02        | 2.23    | 0.90       | 1.00| u26x1   |
| E7 | 20.24 | 1.59        | 3.61    | 0.32       | 0.79| u26xq   |
| E8 | 18.01 | 1.29        | 3.13    | 0.88       | 0.87| u26xj   |
| E9 | 20.27 | 1.13        | 3.14    | 0.29       | 1.00| u26xj   |
| E10| 19.33 | 0.94        | 2.92    | 0.32       | 1.00| u26xj   |
| E11| 20.61 | 1.18        | 2.91    | 0.19       | 0.83| u26xi   |
| E12| 20.08 | 1.95        | 3.49    | 0.53       | 1.00| u26xg   |
| E13| 17.20 | 1.14        | 2.66    | 0.13       | 1.00| u26xd   |
| E14| 20.38 | 1.53        | 3.39    | 0.34       | 0.85| u26xd   |
| E15| 20.69 | 1.14        | 1.95    | 0.58       | 1.00| u26xc   |

disks and there is a fairly good agreement with spectral evolution models [Bruzual & Charlot 1998], using a formation redshift $z_F = 5$ and taking into account a sensible range in metallicities ($0.2 < Z/Z_\odot < 2.5$), which is equivalent to assuming a range in formation redshift, keeping a fixed metallicity. A simple photometric redshift estimation was done, giving a median redshift $z \sim 0.2$ which is reasonable given the completeness level of the $K$ band images. A further analysis along these lines would require fluxes in additional bands.

In agreement with previous observations, we found spheroids appear bluer than the model prediction for passive evolution, clearly showing the existence of ongoing star formation, similarly to the blueness detected in some cluster ellipticals. Further study of this epoch of possibly strong star formation in the life of early-type galaxies will be of great importance in the understanding of galaxy formation.

In order to compare our results with previous NIR surveys in MDS fields [Glazebrook et al. 1998], figure 7 shows the histogram of objects detected in $I$ and $K$ along with the data from Glazebrook et al. cutting their list at our completeness level. There is very good agreement between both surveys, normalising to the same area. A rank correlation test applied to both histograms yield a 100% confidence level. It is also interesting to notice that the extra objects in Glazebrook’s sample as they go deeper in $K$ appear blueward of the peak, signalling the existence of galaxies with a stronger star formation rate, as expected for higher redshift galaxies.

Finally, a search for EROs was undertaken on the overlapping 89.4 arcmin$^2$ region which had photometry in $V, I,$ and $K$. The whole sample down to $K = 18$ had counterparts in the F814W frames, all with un conspicuous $I - K < 4.5$ colours. Hence, no ERO was found, yielding an upper limit for the number density of roughly $dN_{ERO}/d\Omega < 0.011$ arcmin$^{-2}$ ($K < 18.0$), which agrees with previous estimates [Hu & Ridgway 1994].

Figure 6. Histogram of the photometric redshift estimated for objects detected in $V, I$ and $K$ using the prediction for $V - K$ and $I - K$ from the models of Bruzual & Charlot (1998). The median redshift is $z_{PHOT} \sim 0.2$

ACKNOWLEDGMENTS

The authors are grateful to the anonymous referee for helpful suggestions, S. F. Sánchez for pointing out valuable hints, J. M. Diego for the help provided during the last run of observations, and P. Saracco for providing us with the number counts data presented in Figure 1. We also acknowledge helpful discussions with F. Hammer and J. Silk. The 2.2m telescope is operated by the Max Planck Institut für Astronomie at the Centro Astronómico Hispano Alemán in Calar Alto (Almería, Spain). The Medium Deep Survey catalogue is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universi-
Figure 7. $I - K$ colour histogram as a function of morphology. The thin line shows the histogram from Glazebrook et al. (1998), which is scaled down to fit the box limits.

ties for Research in Astronomy, Inc., under NASA contract NAS5-26555. The Medium-Deep Survey is funded by STScI grant GO2684. I.F. acknowledges a Ph.D. scholarship from the 'Gobierno de Cantabria'. N.B. is supported by a Basque Government fellowship. The authors acknowledge financial support from the Spanish DGES under contract PB95-0041.

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