

# An imaging *K*-band survey – II. The redshift survey and galaxy evolution in the infrared

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Accepted 1995 February 23. Received 1995 February 23; in original form 1994 September 16

## ABSTRACT

We present further results from an imaging *K*-band survey of 552 arcmin<sup>2</sup>, complete to a 5 $\sigma$  limit of  $K \simeq 17.3$ . This paper describes a redshift survey of 124 galaxies, and addresses the colours of faint galaxies and the evolution of the *K*-band luminosity function. The optical-to-infrared colours are consistent with the range expected from synthetic galaxy spectra, although there are some cases of very red nuclei. These may possibly be attributed to either extinction or metallicity gradients. Our data show no evidence for evolution of the *K*-band luminosity function at  $z < 0.5$ , and the results are well described by a Schechter function with  $M_K^* = -22.75 \pm 0.13 + 5 \log_{10} h$  and  $\phi^* = 0.026 \pm 0.003 h^3 \text{ Mpc}^{-3}$ . This is a somewhat higher normalization than has been found by previous workers, and it removes much of the excess in faint *K* and *b<sub>j</sub>* counts with respect to a no-evolution model. However, we do find evidence for evolution at  $z > 0.5$ :  $M_K^*$  is approximately 0.75 mag brighter at  $z = 1$ . This luminosity evolution is balanced by a reduced normalization at high redshift: the total luminosity density is required to be approximately constant in order not to exceed the faint counts. The overall evolution is thus *opposite* to that expected in simple merger-dominated models; we briefly consider possible interpretations of this result.

**Key words:** surveys – galaxies: distances and redshifts – galaxies: evolution – galaxies: luminosity function, mass function – infrared: general.

## 1 INTRODUCTION

The development of two-dimensional near-infrared detectors has finally made it possible to survey substantial areas of the sky at these wavelengths to cosmologically interesting depths. Two surveys covering more than several hundred arcmin<sup>2</sup> of the sky have recently been completed: the Hawaii Surveys described by Gardner, Cowie & Wainscoat (1993), Cowie et al. (1994) and Songaila et al. (1994), and the Edinburgh Survey described by Glazebrook et al. (1994 – hereafter referred to as Paper I).

This is the second paper concerning our *K*-band redshift survey covering 552 arcmin<sup>2</sup>. Paper I discussed in detail the construction and calibration of this survey, and the associated optical CCD imaging for all the fields. It also presented our results for the *K*-band star and galaxy counts. This paper is concerned with a *K*-selected redshift survey and the resulting colour-redshift and luminosity function analyses.

A study of galaxy evolution in the near-infrared is of great interest. Historically the main evidence for bulk evolution in samples of field galaxies derives from optical surveys, culmi-

nating in the ‘faint blue galaxy problem’: number-magnitude counts over  $15 < b_j < 28$  are much steeper than predicted by a non-evolving model (see Ellis 1990 for a review). Optically selected redshift surveys have shown this faint excess to be a population of very blue objects, evolved mainly in density rather than blue luminosity (Broadhurst, Ellis & Shanks 1988; Colless et al. 1991; Glazebrook et al. 1995a). Various models have been proposed to explain this observation: Koo, Gronwall & Bruzual (1993) have proposed radical alteration of the local luminosity function by introducing a large dwarf galaxy component. Similarly, Cowie, Songaila & Hu (1991) and Babul & Rees (1992) have proposed a model in which the blue population consists of a new population of dwarf galaxies undergoing an initial starburst at  $z \sim 0.4$  and fading to invisibility by the present day. A different model has been proposed by Broadhurst, Ellis & Glazebrook (1992: BEG) and Rocca-Volmerange & Guiderdoni (1990) in which a large amount of galaxy-galaxy merging has occurred in the field population in the recent past, as might be expected in CDM-like theories in which structure develops by hierarchical growth (e.g. Carlberg 1992). However, the most recent possible explanation

is the simplest: that bright surveys are not sufficiently sensitive to galaxies of low surface brightness (McGaugh 1994). This suggestion of incompleteness in the bright counts accords with the work of Metcalfe et al. (1991, 1995), who have argued that the fainter data for  $17 < b_i < 22$  can then be explained by a high local normalization to the luminosity function.

In view of these controversies, an independent approach to galaxy evolution is clearly attractive, and the *K* band is in many ways preferable to the optical. The optical work samples the rest-frame UV at  $z \gtrsim 0.3$ , so that the optical luminosity depends sensitively on the rate of star formation. Also, most of the optical light in galaxies comes from massive OB stars which are only a small fraction of the total stellar mass of the galaxy. Thus a dwarf galaxy undergoing a powerful starburst can attain a  $b_i$  luminosity identical to that of a giant spiral or elliptical galaxy evolving quiescently. Since galaxies at high redshift are unresolved from the ground, these very dissimilar systems can be indistinguishable in faint optical imaging data.

In contrast, the near-infrared light in galaxies is produced by giants drawn from the population of old evolved stars which dominate the stellar mass. Moreover, the *K*-correction is much better defined for a *K*-band sample than in the optical. This is again because the spectral slope in the optical is dominated by the star-formation rate; thus spiral and elliptical galaxies have blue *K*-corrections that differ by 1 mag at  $z = 0.5$ . The observed morphological mix will therefore change greatly with redshift, complicating the interpretation. In contrast, galaxy colours in the near-infrared are dominated by old stars and are uniform across Hubble types (Aaronson 1978), thus yielding a constant morphological mix.

A no-evolution prediction showed that we expected to see galaxies out to  $z = 1$  at  $K = 17$  (Paper I), the redshift of interest for evolution, so this motivated us to carry out a redshift survey of our Paper I objects. Additionally, the colour-redshift relation allows us to test generic properties of spectral evolution models independently of the luminosity function.

The plan of this paper is as follows. Section 2 discusses the spectroscopic observations and the data reduction procedures used to obtain the redshifts, and Section 3 describes how we use these to obtain revised *K* magnitudes in metric apertures for our galaxies. In Section 4 we discuss the details of the faint galaxy colours and how they depend on redshift. Section 5 details our luminosity function analysis and in Section 6 we compare our results with other work on galaxy evolution. Finally the results and conclusions are summarized in Section 7.

Throughout, we scale results to the usual dimensionless Hubble parameter:  $h \equiv H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Unless otherwise stated, we assume a cosmological model with  $\Omega = 1$  and zero cosmological constant.

## 2 SPECTROSCOPIC OBSERVATIONS

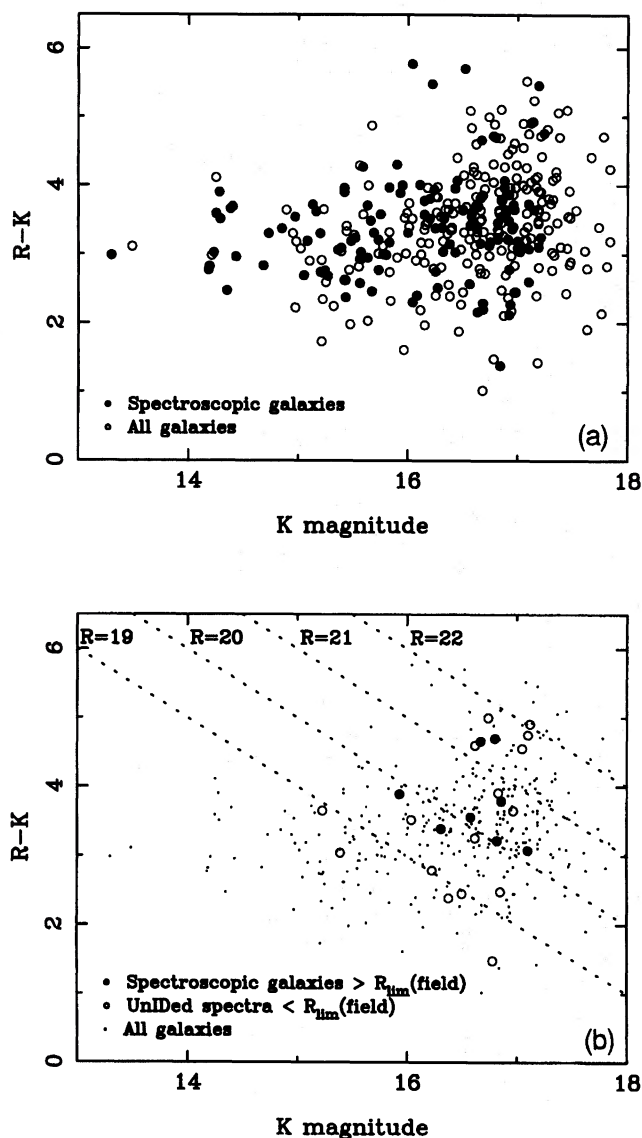
Our redshift survey was carried out in several observing runs on the Anglo-Australian Telescope and the William Herschel Telescope in La Palma over the period 1990–1992. We used the Autofib multi-fibre spectrograph (Parry & Sharples 1988) for the brighter objects ( $R < 19$ ), long- and multi-slit spectroscopy using the ISIS spectrograph for intermediate magnitudes ( $18 <$

$R < 20$ ) and the LDSS1 (Wynne & Worswick 1988) and LDSS2 (Allington-Smith et al. 1994) multi-slit spectrographs (both of which have a very similar design) for the very faintest objects with  $R \gtrsim 20$ .

We followed standard procedures for debiasing, flat-fielding and stacking the data and extracting spectra. Our final spectra were determined to be limited by Poisson sky noise. For our faintest objects at  $R = 21$ – $22$ , 9000-s integrations were required to give  $> 90$  per cent completeness in identifications. We determined the identifications manually by carefully examining each individual spectrum, and also used cross-correlation with galaxy templates following Tonry & Davis (1979). This confirmed our manual results, but proved no more powerful at extracting redshifts from faint noisy spectra than the manual method. In our initial spectroscopic runs we observed objects which we had classified as stars from the image profiles in our broad-band CCD images; it turned out that our classification was very reliable (for the statistics see Paper I) and so we subsequently observed only objects classified as galaxies. Our final redshift catalogue consists of 124 galaxies and is presented in Table A1 of the appendix.

As a result of an observing programme which evolved through a succession of spectrographs of increasing sensitivity, our dataset was acquired in a somewhat heterogeneous manner. An ideal approach would have been to define in advance a target sample which was randomly selected from the parent catalogue to contain uniform numbers of objects per *K* magnitude bin, and continue observing until redshifts for all the target objects were obtained. In practice, the targets that we could observe were limited by scheduling of observing runs and by weather. The initial runs lacked sufficient sensitivity to yield redshifts for the reddest objects, and so there were initially many cases of inconclusive spectra. As the survey progressed and more sensitive spectrographs became available, we were able to obtain successful spectra representative of the previous class of failures, although we could not in all cases observe the identical objects. Our final spectroscopic runs were therefore used to ensure that the redshift sample was as statistically representative as possible. The  $(K, R - K)$  colour-magnitude diagram was inspected, and targets were chosen randomly to fill in under-sampled parts of the  $(K, R - K)$  plane. The success of this strategy may be judged from Fig. 1(a), where we compare the  $(K, R - K)$  distribution of the objects with redshifts with that for all the galaxies. We are very close to the desired uniform sampling of  $R - K$  at given *K*, down to  $K = 17.25$ ; fainter objects were not considered. The only areas where the eye suggests a low sampling are at  $(K, R - K) \simeq (17.0, 4.5)$  and  $(K, R - K) \simeq (15.5, 2.0)$ . The former case reflects the difficulty of obtaining spectra for very faint objects, and is quantified by the colour-dependent weights discussed in Section 5.1. Conversely, any suggestion of bias against the blue objects is merely a random fluctuation. Most spectra come from our October fields, and redshifts were obtained for the bluest objects in these fields; however, the March fields contain a few galaxies that are bluer than any in the October fields.

Since not all spectra yielded a redshift, it is important to be sure that the omitted objects do not bias the results. Our early runs on less sensitive spectrographs had many inconclusive spectra, but this mainly allowed us to establish empirically the integration time needed for an object with a given *R*-band magnitude. For each spectroscopic run, we



**Figure 1.** (a) The  $R-K$  versus  $K$  colour-magnitude plane for our survey. The open circles show all the data, with spectroscopic sample members being indicated by solid points. Data from both March and October fields are included, although a correction to the former is made so that the magnitudes refer to 4-arcsec diameter apertures (see Section 3). Brightwards of the spectroscopic selection at  $K = 17.25$ , the sampling of colour at fixed  $K$  is very close to uniform. (b) The same as panel (a), but now the points represent all galaxies, the open circles show the 16 unidentified spectra that are brighter than the appropriate optical completeness limits defined for the spectroscopic runs, and the solid circles show the 8 identified spectroscopic galaxies that lie fainter than the completeness limits. These are almost all within 0.5 mag of the relevant optical limit; our assumption is that these are merely slightly degraded versions of our successful spectra, and that their omission does not bias the results. The dotted lines show the loci of constant  $R$  magnitude in this diagram.

therefore defined a target integration time based on the  $R$ -band magnitude. For the different instruments involved, this corresponded to a limiting magnitude in a 10 000-s integration of approximately  $R = 19.0$  (Autofib);  $R = 21.0$  (LDSS1);  $R = 20.8$  (ISIS);  $R \gtrsim 22.5$  (LDSS2). This resulted in 16 objects that satisfied our integration-time criteria based on their  $R$  magnitude, but for which no redshift was obtained.

The locations of these objects on the colour-magnitude plane are shown in Fig. 1(b). In almost all cases, the objects were within 0.5 mag of the effective optical limit for the instrument involved, and so it is plausible that they are simply low signal-to-noise ratio versions of the successful spectra, a selection of which are shown in Fig. A1 in the appendix. Moreover, it is clear from Fig. 1(b) that there is no significant bias in colour or magnitude with respect to either the spectroscopically identified galaxies or the larger sample of image-classified galaxies. Given this and the small number of such objects, we believe it is reasonable to assume that the redshift distribution is not biased by their omission from the sample. Conversely, as in any spectroscopic sample, there are also a small number of identified galaxies fainter than our nominal limits: these are also shown in Fig. 1(b). There are only 8 of these (numbers 77, 118, 132, 190, 316, 333, 362, 364); again they are within 0.5 mag of our completeness limits and they lie in typical locations in the  $(K, z)$  diagram; their inclusion makes no significant difference to our subsequent analyses.

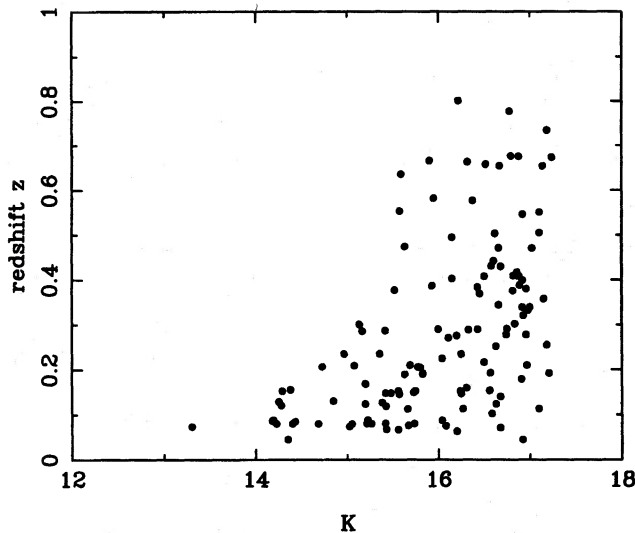
In summary, our spectroscopic sample contains 124 of the 335 galaxies in the imaging survey of Paper I. Most of our redshifts (119) are from the October fields, which contain a total of 201 galaxies, and we therefore have 59 per cent sampling in this region. Furthermore, the selection of objects has been adjusted so as to give a representative coverage of the  $(K, R-K)$  plane (apart from a known reduced sampling at faint  $K$ ). Our sample should be statistically representative of the infrared galaxy population.

Fig. 2 shows the fundamental data in the form of the redshift-magnitude plane. It is interesting to note that substantial redshifts are attained at relatively bright magnitudes. This observation already anticipates one of our principal conclusions: that ‘merger’ models which postulate a faint characteristic luminosity at high redshift are difficult to reconcile with our data.

### 3 APERTURE CORRECTIONS

An important issue not fully explored in Paper I or by Gardner et al. (1993) is the issue of aperture corrections to the data. The majority of our data were measured through a 4-arcsec diameter aperture, although some (the March fields) used 8 arcsec. An aperture of about 6 arcsec was used for most of the Hawaii work (see Gardner 1992). In their recent paper on the  $K$ -band luminosity function, Mobasher, Ellis & Sharples (1993) corrected all their data to a standard isophotal aperture based on the optical light profiles of their galaxies. The metric aperture involved varied, but was typically 20–30  $h^{-1}$  kpc, which would only correspond to our 4-arcsec aperture at redshifts of  $z \approx 1$ . Our magnitudes are thus systematically fainter than those defined by other workers; how much difference does this make?

With redshifts secured we are now able to remeasure magnitudes through metric apertures; we will use a standard aperture of 20  $h^{-1}$  kpc, which should be close to total for most galaxies and is a typical diameter for local measurements. For large apertures ( $\gtrsim 10$  arcsec) our  $K$  magnitudes start to become unreliable due to noise and flat-field effects (due to the small size of the IRCAM detector). We therefore follow the  $K$  growth curves out to where they turn over, or become too noisy ( $\Delta K < 0.2$ ); beyond this we adopt the growth curve



**Figure 2.** Redshift against  $K$  magnitude for the spectroscopic sample. Note that the sample probes to substantial redshifts  $z_{\max} = 0.8$ , and that the high-redshift bins contain a number of relatively bright galaxies, as bright at  $K \simeq 15.5$  at  $z = 0.6$ .

for the same galaxy from the corresponding  $R$ -band CCD image. This is much better defined out to very large apertures. Fig. 3 shows the difference between the original 4-arcsec  $K$  magnitudes and the  $20 h^{-1}$  kpc magnitudes as a function of redshift for galaxies for which a  $20 h^{-1}$  kpc magnitude is directly measurable from the growth curves. As expected the low-redshift galaxies are systematically too faint, by up to 1 mag.

We might expect the growth in metric luminosity to be well parametrized following the approach of Gunn & Oke (1975) as:

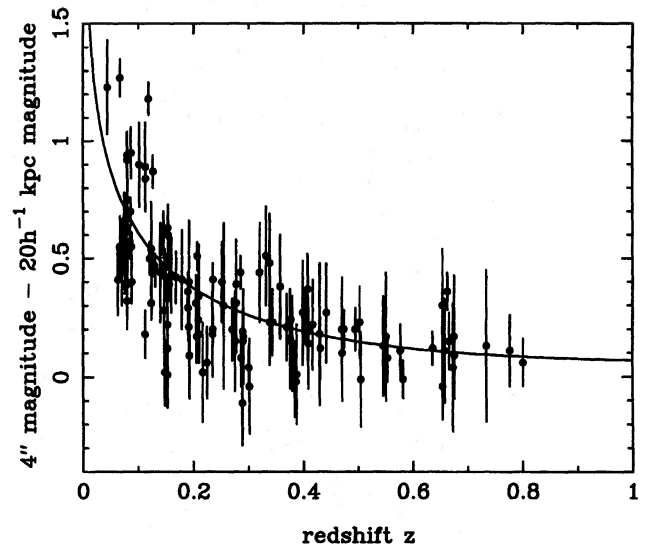
$$L(< r) \propto r^{\alpha}. \quad (1)$$

For brightest cluster galaxies,  $\alpha \simeq 0.7$  (Schneider, Gunn & Hoessel 1983), but lower values are more appropriate for field galaxies in general. For the sample of Mobasher et al. (1993), typical effective values are  $\alpha \simeq 0.4$ , and this is consistent with the Hawaii data (Gardner 1992). We would expect such a power-law profile to be valid provided it is not assumed to hold over too large a range of scales. Our maximum redshift is 0.8, and all but two have  $z > 0.06$ ; the range of proper diameters corresponding to our 4-arcsec apertures is thus 3.2 to 16.5  $h^{-1}$  kpc. Even over this large range, exponential profiles ( $r_{\text{scale}} = 3 h^{-1}$  kpc) and  $r^{1/4}$  profiles ( $r_{\text{eff}} = 4 h^{-1}$  kpc) deviate from the power-law model at only at the  $\simeq 0.2$ -mag level. We plot the  $r^{0.4}$  prediction in Fig. 3; it is an excellent parametrization of the data.

Our final metric magnitudes in  $K$  and  $R$  are given in Table A1. We carried out luminosity function analyses using both these values and those predicted from the 4-arcsec data using the  $r^{0.4}$  growth curve. The results were indistinguishable, as expected from the good agreement shown in Fig. 3.

#### 4 FAINT GALAXY COLOURS

We begin by looking at the optical-infrared colours of our data. This will allow us to assess the mix of Hubble types in this sample, as well as to test synthetic galaxy spectra, on



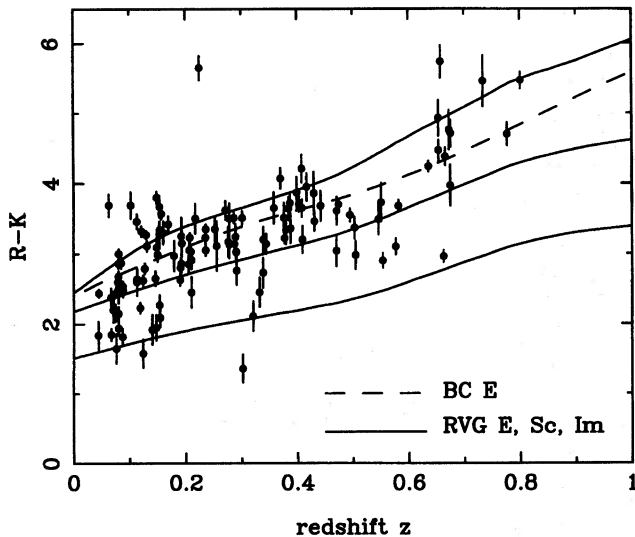
**Figure 3.** The difference between our published 4-arcsec  $K$  magnitudes and the new direct determinations of the magnitudes in a  $20 h^{-1}$  kpc aperture. The error bars are those for the larger aperture measurement. The solid line shows the behaviour expected for the adopted  $r^{0.4}$  growth curve. This simple a priori model is an excellent fit to the data, and clearly introduces systematic errors no larger than about 0.1 mag.

which we will rely to  $K$ -correct the data in the luminosity function analysis.

For the colours we measure  $K$  and  $R$  magnitudes independently in  $20 h^{-1}$  kpc apertures as in Section 3. Fig. 4 shows the  $R - K$  colours of the galaxies plotted against redshift. We compare the colours with those of the galaxy templates we used for the number count predictions in Paper I (from Rocca-Volmerange & Guiderdoni 1988; RVG), plotting the red envelope for a high-redshift 1-Gyr burst of star formation, which should provide an upper limit to the locus of elliptical galaxies. We also show the intermediate-colour Sc type and the Im type, which should define the blue limit for galaxies on the Hubble sequence. For a  $K$ -selected survey the  $K$ -corrections are very similar (see Section 5.2) for all types and so the morphological mix should not change with redshift. It is evident from Fig. 4 that the mix, as defined by colour, is indeed approximately unchanging and so, unlike optical surveys, we are not biased against high-redshift red galaxies.

We also consider the more recent evolutionary synthesis models of Bruzual & Charlot (1993; BC). These use a more up-to-date library of stellar templates and compute with a more accurate isochrone synthesis technique. Particularly important for our application is that the infrared portions of the spectra are based on much more detailed data than the work of RVG. Fig. 4 also shows the BC version of the 1-Gyr burst, which makes a similar prediction for the red envelope, but is systematically slightly bluer than the RVG model. The latter seems in practice to be in better agreement with the data.

We note the existence of one object (ID #96) with very extreme colours ( $z = 0.225$ ,  $R - K = 5.7$ ). This object has an emission line spectrum and at this redshift the  $\text{Pa}\alpha$  line lies in the  $K$  window; could this contribute to the  $K$  flux? Given standard case B assumptions for hydrogen line ratios (Hummer & Storey 1987),  $\text{Pa}\alpha/\text{H}\beta = 0.332$ , and we estimate from the observed  $\text{H}\beta$  flux that the line flux from  $\text{Pa}\alpha$  would



**Figure 4.** The  $R-K$  versus  $z$  colour-redshift distribution. The solid lines (top to bottom) show the loci of the old burst model (providing a red envelope for ellipticals) and Hubble Sc and Im types from RVG. Also shown for comparison (dashed) is the old burst model from BC.

be equivalent to  $K = 27$ . There would thus need to be large amounts of extinction in order for line emission to be significant, but this is not indicated in the optical spectrum. This object merits further study.

Otherwise, the reddest galaxies are approximately consistent with the model red envelope to within observational error, with the possible exceptions of #109, #224 and #346. This was not the case with our first version of this diagram for 4-arcsec aperture colours, which contained many galaxies with  $z < 0.3$  much redder than the envelope, particularly at low redshift. This was initially puzzling, but it was eventually realized that this was an effect of colour gradients: at low redshifts, the 4-arcsec apertures sample the galaxy nuclei only – and these are very red in some cases. The galaxies with particularly red nuclei, together with their redshifts and 4-arcsec colours, are: #224, #563, #406, #109, #392 and #334;  $z = (0.063, 0.080, 0.121, 0.148, 0.153, 0.192)$ ;  $R-K = (3.8, 3.7, 3.9, 4.0, 3.9, 4.0)$ . Significant optical-infrared colour gradients in ellipticals were previously noted by Peletier, Valentijn & Jameson (1989). They find up to 0.6 mag of reddening in  $V-K$  for a factor 10 in radius, and our results seem to be consistent with these more extreme values.

What is the cause of the red nuclei? Although galactic bulges are redder than discs, we still would not expect them to be redder than a 1-Gyr burst if the colours were due to the stellar populations. It is possible with the BC code to choose various initial mass functions (IMFs), and it is interesting to ask if the results are robust, particularly for the red envelope. We find that stars with initial masses  $> 2.5 M_{\odot}$  make negligible contributions at late epochs ( $> 15$  Gyr). Increasing the proportion of low-mass stars by adopting a flatter IMF also makes little difference – doubling the fraction of stars below  $0.3 M_{\odot}$  only makes a difference to the curve at the 0.05-mag level. We conclude that the choice of IMF has little influence on the red envelope of  $R-K$  colours, as it is determined by the spectral energy distributions of  $\sim$  solar mass stars. Peletier et al. attribute the reddening to metallicity gradients. This is certainly a plausible explanation for our results, although large amounts of dust in some

nuclei remain a possibility (a screen with  $A_V = 1.2-1.3$  mag would be required to produce the observed  $R-K$  excess). Low-level AGN are a third potential explanation, especially if they are heavily reddened. These extremely red galaxies merit detailed further examination to investigate these possibilities.

## 5 LUMINOSITY FUNCTION ANALYSIS

We now proceed to derive the K-band galaxy luminosity function from our data. We shall be particularly interested in the comparison between our results and those of Mobasher et al. (1993) and the Hawaii survey (Cowie & Songaila 1993; Cowie, Songaila & Hu 1995). The former was based on K-band observations of 95 B-selected galaxies, with completeness claimed to  $K = 12.5$ . The Hawaii sample consists of 262 redshifts, complete to  $K \simeq 19-20$ . In fact, our results turn out not to agree very well with either of these pieces of work, for what we believe are the reasons described below in Section 5.4.

### 5.1 Counts and incompleteness corrections

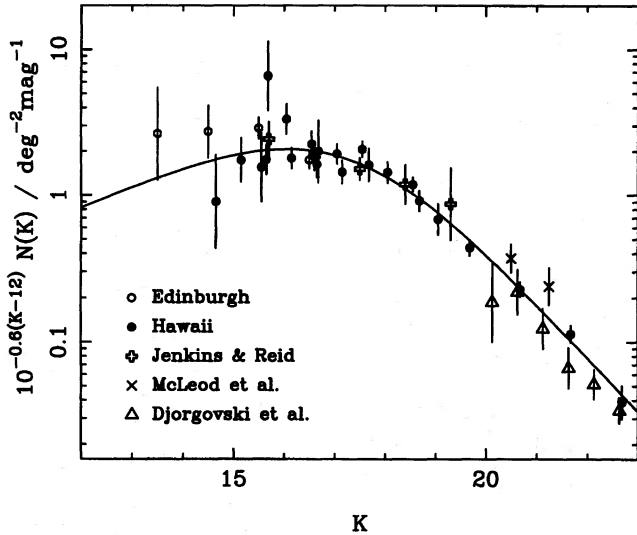
The longer integration times required mean that we were able to obtain fewer spectra for the fainter galaxies. Nevertheless, the redshift distribution at given magnitude should still be faithfully reproduced by our data, provided the range of colours at given  $K$  is properly sampled. We tested this by dividing the  $(R-K) - K$  colour-magnitude plane into cells (using increments of 0.3 in  $K$  and 0.5 in  $R-K$ ) and comparing the populations of these cells in our total and spectroscopic samples. This allows a colour-dependent weight to be deduced at given  $K$  magnitude. These weights were usually close to unity; setting them to exactly unity had no significant effect on the results below – the maximum change in  $M_K^*$  is only 0.02 mag and the effect on the resultant space densities is at the  $\lesssim 10$  per cent level. As the latter span a factor of 100 in value it is not surprising that  $M_K^*$  is robust to such changes.

We now need to know the effective  $K$ -dependent incompleteness, and this may be deduced by comparing the number of galaxies in our spectroscopic sample as a function of magnitude with that expected from the overall number counts. A convenient analytical fit for these is

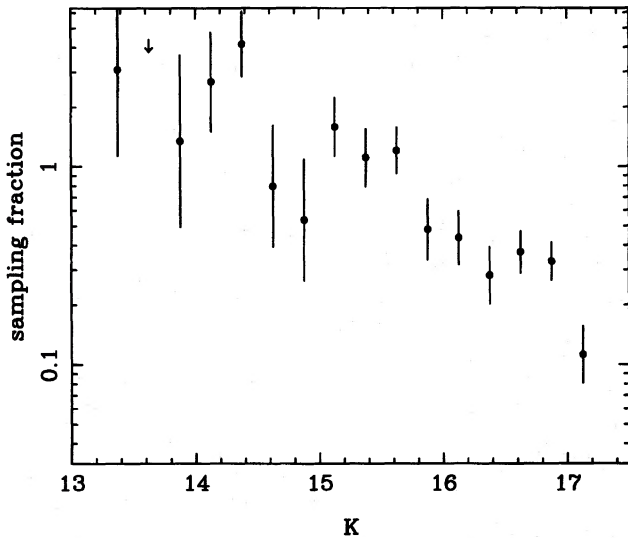
$$\frac{dN}{dK} / \text{deg}^{-2} = \frac{10^{0.75(K-12.1)}}{[1 + 10^{0.35(K-17.2)}]^{1.5}}, \quad (2)$$

which is a statistically acceptable best fit to the data from Paper I plus the Hawaii counts from Gardner et al. (1993), and the data of Jenkins & Reid (1991), as shown in Fig. 5 (this plot also includes the recent faint count data from McLeod et al. 1995 and Djorgovski et al. 1995). We have preferred to force the slope at bright  $K$  magnitudes to the Euclidean value expected from the aperture correction:  $N \propto 10^{\beta K}$ , where  $\beta = 1.2/(2-\alpha)$  (where  $L \propto r^{\alpha}$  is the analytic aperture correction derived in Section 3); any other slope would indicate strong local evolution if taken literally.

The corrections needed to achieve uniform 4-arcsec magnitudes in Fig. 5 are as follows. The Hawaii data (Gardner 1992) were measured in 6.3-arcsec apertures for the Hawaii



**Figure 5.** The  $K$ -band number counts, normalized to the usual Euclidean slope. The smooth analytic fit described in the text is statistically consistent with all the measurements, showing that the counts are well determined. All data have been corrected to 4-arcsec diameter aperture magnitudes, as described in the text.



**Figure 6.** The 'completeness' of our spectroscopic sample, expressed as a ratio of the observed number of galaxies in a bin to the number predicted by our count fitting formula for  $552 \text{ arcmin}^2$ . We assume that the redshift distribution at given  $K$  is unbiased in our sample, and that the sampling fraction shown here may be used to correct our sample to be representative of one complete to  $K = 17.25$ . Note that the apparently unphysical values exceeding unity are reasonable: some bright galaxies were inadvertently selected as astrometric reference 'stars', so these bins are biased high.

Medium Deep and Hawaii Medium Wide Surveys, but published with offsets of respectively  $-0.1$  and  $-0.2$  mag as a notional correction to total. We have removed these offsets and added a further  $0.2$  mag to correct to 4-arcsec measurements. The deeper Hawaii Deep Survey was measured in 3.5-arcsec apertures and a correction to 6 arcsec made on a field-to-field basis. Since the individual corrections are not available, we have treated the published data as exact 6-arcsec measurements and added a correction of  $0.18$  mag. The deep

data of Djorgovski et al. (1995) are in 5.4-arcsec apertures, and so need a correction of  $0.13$  mag. The deep data of McLeod et al. (1995) are 'total' magnitudes from the FOCAS software package (Valdes 1982) for which an aperture is not quoted; we have left them uncorrected. Lastly, for the 20-arcsec apertures used by Jenkins & Reid (1991), the correction to 4 arcsec predicted by our  $r^{0.4}$  growth curve is  $0.70$  mag. This explains why their counts were clearly seen in Paper I to lie above those obtained by other workers. However, we do not expect a power law to apply over this range of radius; at faint magnitudes, apertures above 8 arcsec will be total. We have therefore applied the offset of  $0.7$  at  $K = 15$ , declining to  $0.3$  at  $K = 19$ . This should be correct to within about  $0.1$  mag.

Dividing the  $K$  counts in our spectroscopic sample by the average counts yields the effective completeness, shown in Fig. 6. This stays close to unity until about  $K = 16$  and then falls to almost  $0.1$  in the  $K = 17 - 17.25$  bin, which is the faintest bin that contains spectroscopic data. The completeness is significantly greater than 1 for  $K \approx 14.5$ , and this reflects the use of some galaxies as positional references in constructing the sample (see Paper I). We shall use this incompleteness curve in the luminosity function analysis, assuming unit completeness for  $K < 14$ . Using a smoothed form of this figure makes no difference to the results.

We can now deduce the properties of a true flux-limited sample to  $K = 17.25$  by appropriately weighting the fainter galaxies. Fig. 7 shows both the raw and weighted redshift histograms for our sample. The observed median redshift of  $0.24$  increases to  $0.35$  after weighting.

## 5.2 K-corrections

In order to obtain absolute magnitudes, we require a knowledge of the luminosity distance  $D_L$ , the  $K$ -band  $K$ -correction  $K(z)$ , and the aperture correction  $A(z)$ :

$$M(z) = m - 5 \log_{10}[D_L/10 \text{ pc}] - K(z) + A(z). \quad (3)$$

For simplicity, we shall throughout quote absolute magnitudes assuming  $h = 1$  for the Hubble parameter. The aperture correction converts the observed aperture magnitudes to some proper diameter. As stated above, we shall choose this to be

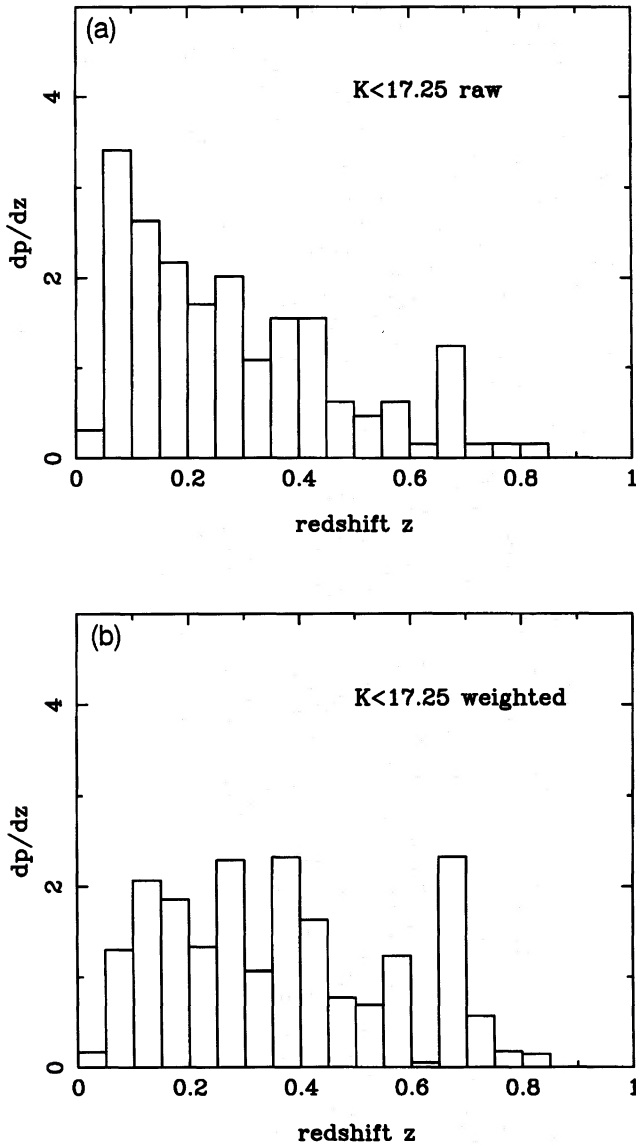
$$D_0 = 20 h^{-1} \text{ kpc}, \quad (4)$$

so that the aperture correction is given in terms of angular-diameter distance  $D_A(z)$  as

$$A(z) = \log_{10}[\theta D_A(z)/20 h^{-1} \text{ kpc}], \quad (5)$$

where  $\theta$  is our standard angular diameter of 4 arcsec.

One of the advantages of the infrared waveband is that the  $K$ -corrections are very similar for all classes of galaxy, reflecting the dominance of giants in this waveband. The widely different amounts of star formation in different Hubble types only affect the spectra at wavelengths somewhat shorter than  $1 \mu\text{m}$ . This is illustrated in Fig. 8, which shows theoretical  $K$ -corrections taken from the evolutionary synthesis models of Bruzual & Charlot (1993). Rather than a range of models designed to fit the Hubble sequence, we show an instantaneous burst of star formation observed at ages from 1 to 10 Gyr. There is satisfyingly little model dependence of the  $K$ -



**Figure 7.** The histograms of redshift for our data. The raw numbers are shown in (a), and (b) gives the result after weighting galaxies to allow for  $K$ -dependent sampling.

corrections. The following is a good fit to the 5-Gyr data for  $z \lesssim 1.5$ :

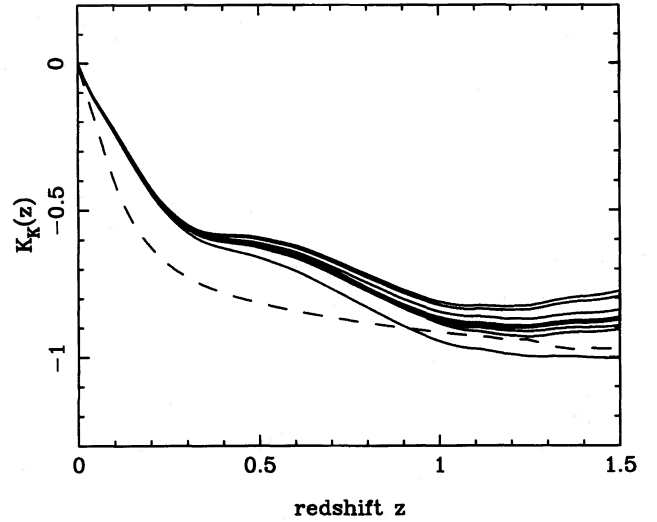
$$K(z) = \frac{-2.58z + 6.67z^2 - 5.73z^3 - 0.42z^4}{1 - 2.36z + 3.82z^2 - 3.53z^3 + 3.35z^4}, \quad (6)$$

and we use this as our standard  $K$ -correction.

For comparison, we also show the  $K$ -correction for the ‘UV-hot’ elliptical model of Rocca-Volmerange & Guiderdoni (1988; RVG). A good fit to their data for  $z \lesssim 1.5$  is

$$K(z) = -(1 + [5z]^{-3/2})^{-2/3}. \quad (7)$$

The BC  $K$ -corrections show more structure than those from RVG, reflecting the less sophisticated treatment of infrared wavelengths by RVG. There is also a systematic difference between the BC and RVG models, of about 0.2 mag at  $z = 0.5$ , in the sense of RVG being bluer (although their models are redder in  $R - K$ ). Our absolute magnitudes would thus be fainter at high redshift by this amount if we adopted the RVG  $K$ -correction. However, we are confident that the BC relation



**Figure 8.** The  $K$ -corrections for the BC models. The solid lines show the behaviour for a delta-function burst of star formation at different ages, from 1 to 10 Gyr (bottom to top). We shall use the 5-Gyr model as the default  $K$ -correction. The satisfyingly near-universal predicted spectral shape in the near-infrared is well evident in this plot. Also shown (dashed) is the UV-hot elliptical model of RVG.

is more nearly correct, since it accounts well for the  $JHK$  colours of local galaxies (Aaronson 1978; Mobasher et al. 1993).

This completes the ingredients needed to deduce absolute magnitudes. We therefore show in Fig. 9 the raw data for the luminosity function analysis: the area of the absolute magnitude-redshift plane sampled by our survey. The following sections analyse this distribution in order to deduce space densities.

### 5.3 Luminosity function estimates

The simplest estimator of the luminosity function is to bin up the data in redshift slices as a function of absolute magnitude. The estimator for the density in a given bin is then the traditional

$$\hat{\phi} = \sum_i \hat{\phi}_i = \sum_i \frac{w_i}{V(z_{\max}) - V(z_{\min})} \quad (8)$$

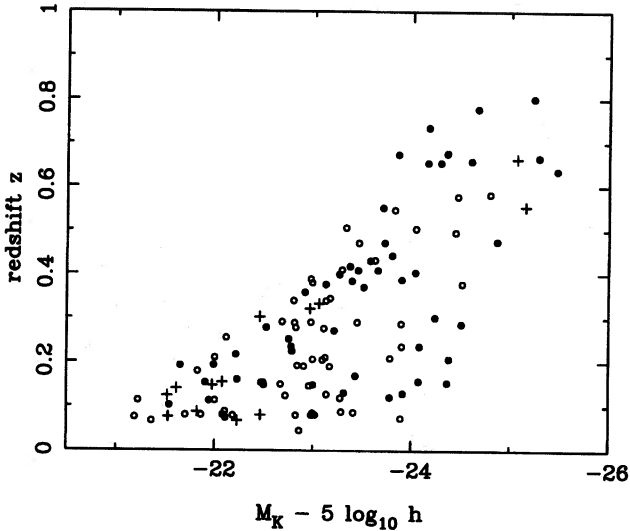
(Felten 1976), where  $z_{\max}$  is the smaller of the maximum redshift within which a given object could have been seen, and the upper limit of the redshift band under consideration;  $z_{\min}$  is the lower limit of the band. In this case, the weight,  $w_i$ , to use is the full product of corrections for colour-dependent incompleteness and reduced sampling at faint  $K$ . The result is shown in Fig. 10(a), for redshift bins 0 – 0.2, 0.2 – 0.4, 0.4 – 0.8.

An alternative way of presenting the same data, which has been favoured by the Hawaii group, is to use the cumulative luminosity density. The obvious estimator for this is

$$\hat{\rho}( > L) = \sum_{L_i > L} L_i \hat{\phi}_i, \quad (9)$$

and the results are shown in Fig 10(b), where luminosities have been converted to solar units on the assumption that the solar luminosity corresponds to  $M_K(\odot) = 3.4$ .

In both cases the message is the same, although the cumulative estimator appears (perhaps misleadingly) less noisy.



**Figure 9.** The apparent magnitude–redshift data of Fig. 2, translated to the absolute magnitude–redshift plane. There is a smooth increase of the maximum luminosity sampled with redshift. However, in order to determine whether this corresponds to an increasing characteristic luminosity, a full luminosity function analysis is required to take account of the sampling volumes as a function of redshift. The different symbols correspond to three equal classes of rest-frame colour: filled circles denote E/Sa; open circles Sb; crosses Sc/Im. Note the fainter characteristic luminosity of the last class.

While the two low- $z$  slices are very similar, it is clear that the characteristic luminosity is higher in the  $0.4 < z < 0.8$  slice, by at least 0.5 mag. It also seems as though the overall luminosity density is very nearly constant.

We now quantify these visual impressions by model fitting. It is convenient to describe the galaxy luminosity function via a Schechter function fit at each redshift:

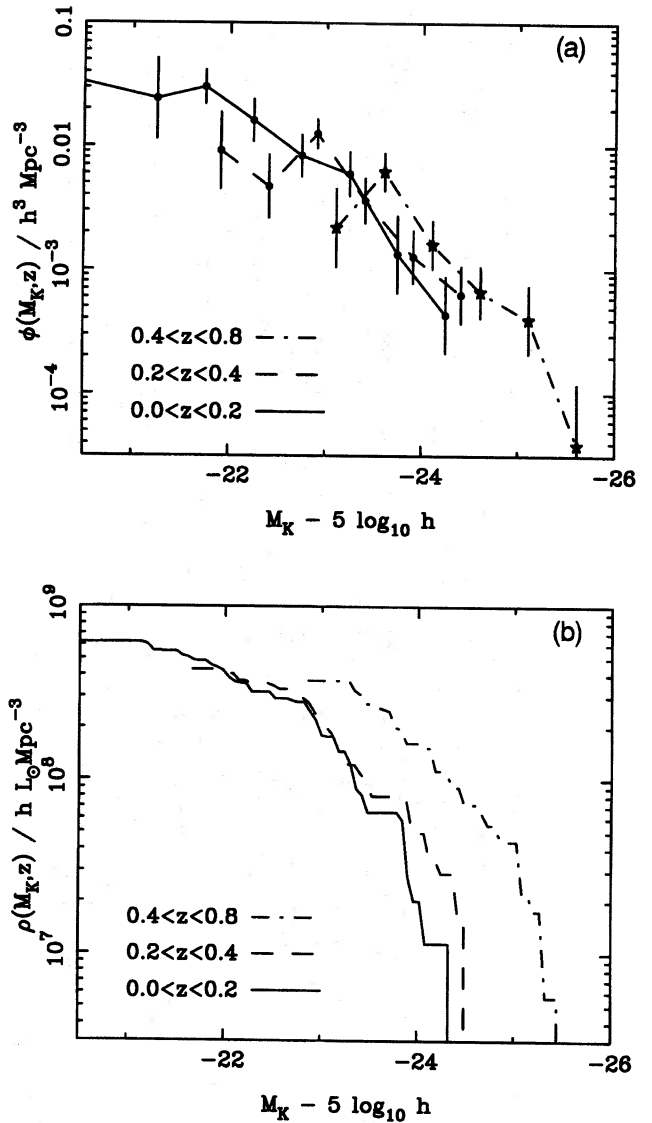
$$d\phi = 0.921 \phi^* (L/L^*)^{\alpha+1} \exp[-L/L^*] dM. \quad (10)$$

The optimal way of fitting such models to moderate discrete datasets such as ours is to use maximum likelihood. In the absence of clustering, one would define likelihood by

$$\mathcal{L} = \prod_i \frac{d^2 p}{dM dz} (M_i, z_i), \quad (11)$$

and extra constraints such as operating over a redshift band can be applied by restricting the product to the relevant objects and normalizing the model probability distribution to the required region of  $(M, z)$  space.

The presence of clustering renders the vertical normalization of the luminosity function uncertain. It may also affect the shape of the function, but such luminosity segregation has never been demonstrated convincingly, and we shall assume here that it is smaller than our statistical errors. It is unclear how good this assumption is in the infrared: the known phenomenon of morphology segregation plus the tendency for ellipticals to be redder than spirals should produce some brightwards shift in characteristic luminosity – so that a positive density perturbation boosts the number density of bright galaxies in two ways. The following method at least avoids the direct density boost, and so should be closer to the average luminosity function. In the end, there is no substitute for an area that is large enough to be representative.



**Figure 10.** The luminosity function results, expressed in two ways: (a) the binned luminosity function; (b) the cumulative luminosity density, assuming  $M_K(\odot) = 3.4$ . Both these methods make the point that there is little evidence for evolution in the luminosity function out to  $z = 0.4$ . At  $0.4 < z < 0.8$ , however, the characteristic luminosity is 0.5–1 mag brighter, with some suggestion that the characteristic density has declined.

The above method can now be applied directly for an infinitesimal redshift band, since only the probability distribution for  $M$  at given  $z$  is involved and amplitude scalings normalize away:

$$\mathcal{L} = \prod_i \frac{dp}{dM} (M_i | z_i). \quad (12)$$

This expression can be immediately generalized to a finite redshift range by continuing to use the conditional probability of  $M$  at given  $z$  – but this must now be normalized individually for each  $z_i$  of interest.

A last problem is how to deal with incompleteness. We have deduced a set of weights  $w_i$  which account for the sampling incompleteness associated with each object, so it is tempt-

**Table 1.** Luminosity function fits.

| $z$       | $M_K^*(z)$        | $\phi^*(z)/h^3 \text{ Mpc}^{-3}$ |
|-----------|-------------------|----------------------------------|
| 0.0 – 0.2 | $-22.72 \pm 0.23$ | $0.029 \pm 0.007$                |
| 0.2 – 0.4 | $-22.85 \pm 0.17$ | $0.020 \pm 0.003$                |
| 0.4 – 0.6 | $-23.23 \pm 0.23$ | $0.013 \pm 0.003$                |
| 0.6 – 0.8 | $-23.68 \pm 0.30$ | $0.009 \pm 0.002$                |
| 0.0 – 0.4 | $-22.75 \pm 0.13$ | $0.026 \pm 0.003$                |
| 0.4 – 0.8 | $-23.41 \pm 0.24$ | $0.011 \pm 0.003$                |
| 0.0 – 0.8 | $-23.01 \pm 0.11$ | $0.019 \pm 0.002$                |

ing to modify the likelihood to

$$\mathcal{L} = \prod_i \left[ \frac{dp}{dM}(M_i | z_i) \right]^{w_i} \quad (13)$$

(e.g. Zucca, Pozzetti & Zamorani 1994). However, although this would eliminate gross biases in the answer, it is clearly not satisfactory statistically. This expression corresponds to counting a few faint objects many times, so that the error bars will be characteristic of a larger sample than the real one – i.e. they will be spuriously small. The correct approach is to incorporate the incompleteness into the model:

$$\mathcal{L} = \prod_i \frac{\phi(M_i, z_i) C(M_i, z_i)}{\int_{-\infty}^{\infty} \phi(M, z_i) C(M, z_i) dM} \quad (14)$$

where the completeness factor  $C$  accounts for sampling factors and magnitude limits, and is incorporated into the normalization. It is easy to deal with our  $K$ -dependent sampling in this way. Any colour dependence is harder to deal with, however, since this does not have a direct relation with  $M$  and  $z$ . We therefore used the  $\mathcal{L} \propto p^w$  prescription for the colour weights only. Since these are unity on average and have a small deviation from unity, the fact that this is not formally the correct procedure will not be a problem in practice. In fact, setting all colour weights to unity has no significant effect on our results.

This method gives a value for the characteristic luminosity in a redshift band,  $L^*(z)$ ; the normalization  $\phi^*(z)$  can then be determined from the overall numbers of objects (although it is still subject to clustering fluctuations). The errors quoted below assume that luminosity density can be measured exactly, so that the fractional error on  $\phi^*$  is the same as that on  $L^*$ . The results of the analysis are given in Table 1, assuming  $\Omega = 1$  and a Schechter-function slope of  $\alpha = -1$  (letting this float yielded a best-fitting value of  $\alpha = -1.04 \pm 0.31$ ).

These numbers paint an interesting picture, and confirm earlier visual impressions. There indeed appears to be some evidence for luminosity evolution in the sense that  $M_K^*$  was brighter in the past. The no-evolution hypothesis is ruled out at about the 4 per cent significance level, considering the variation of  $M_K^*$  alone. On the other hand, there is no evidence for evolution for  $z < 0.6$ . Furthermore, there is evidence that the overall normalization of the luminosity function is a declining function of redshift.

A simple model that accounts for what is seen is therefore to take the low- $z$  parameters for the luminosity function,

$$M_K^*(0) = -22.8; \quad \phi^*(0) = 0.026 h^3 \text{ Mpc}^{-3}, \quad (15)$$

and scale them approximately as  $L^* \propto (1+z)$  and  $\phi^* \propto (1+z)^{-1}$ . This looks very like the merging models advocated

by Broadhurst et al. (1992), with an approximately conserved luminosity density – except that the evolution is in the opposite sense.

These results are derived on the assumption of an Einstein–de Sitter model. Since we have made aperture corrections that involve fixed metric diameters, the whole analysis should in principle be re-done from the start for any different model. However, since the aperture corrections are only important at low redshift, it will suffice to ask how the luminosity distance and volume element change for different models. To illustrate the model sensitivity, we focus on  $z = 0.7$ , which is the centre of our highest- $z$  bin. We consider two popular alternative models: (A) an open universe with  $\Omega = 0.2$ ; (B) a  $k = 0$  model with  $\Omega = 0.2$  in matter and  $\Omega = 0.8$  in vacuum energy. The required distances and volumes, divided by those for the Einstein–de Sitter model, are  $D_L(0.7) = 1.14$  (A) and  $1.32$  (B);  $dV(0.7) = 1.60$  (A) and  $2.89$  (B). Adoption of these models would thus exacerbate the trends we have identified:  $M^*$  at high redshift would be  $0.3 - 0.6$  mag brighter, and  $\phi^*$  would be a factor  $1.6 - 2.9$  lower. Note that the total luminosity density would decline only slightly: this is a relatively robust quantity.

Lastly, we consider the question of dependence of the luminosity function on colour. Using the colour-redshift plot of Fig. 4, it is possible to divide the sample at approximate Hubble-type boundaries by simple vertical shifting of any of the model lines. We have partitioned the sample into three equal parts in this way, and galaxies of different colour are indicated by different symbols in Fig. 9. Restricting attention to  $z < 0.5$ , where the overall sample has no evidence for evolution, we find the following  $M^*$  values (assuming  $\alpha = -1$ ):  $-22.85 \pm 0.18$  (reddest: approximately E/Sa);  $-22.92 \pm 0.18$  (intermediate: approximately Sb);  $-21.32 \pm 0.28$  (bluest: approximately Sc/Im). There is thus a strong trend for the bluest galaxies to be less luminous. However, in agreement with Mobasher et al. (1993), we find little difference between  $M^*$  for the two reddest categories: ellipticals and early-type spirals.

#### 5.4 Comparison with other results

These numbers are very different from the results of Mobasher et al. (1993), who (for  $h = 1$ ) obtained  $M^* = -23.6 \pm 0.3$  and  $\phi^* = 0.0046 \pm 0.0011$ . How can it be that we have obtained a characteristic luminosity a magnitude fainter and a normalization over 5 times higher? It sounds like there is some error, but the numbers are not as different as they seem. Mobasher et al. used isophotal magnitudes, rather than a fixed metric aperture. If we consider their objects with  $z \simeq 0.1$  (the highest redshift objects, which are the most luminous and which thus dominate the determination of  $M^*$ ), their median aperture is of approximately  $40 h^{-1}$  kpc diameter, which immediately makes their magnitudes  $0.3$  mag brighter than ours, if we adhere to the power-law aperture correction. Also, the  $K$ -corrections used are different: they adopt  $K_K(z) = -0.7z + 3.9z^2$ , a much weaker dependence than our  $K_K(z) \simeq -2.58z$ . At  $z = 0.1$ , the difference in  $K$ -correction is  $0.22$ , so that this plus the aperture difference accounts for  $0.52$  mag of the  $0.8$ -mag difference in  $M^*$ ; the remaining difference is not statistically significant. As for the difference in  $\phi^*$ , this may well be partly due to density fluctuations, but it is also possible that the Mobasher et al. sample is systematically incomplete: since their data

were based on infrared measurements of blue-selected galaxies, the population of very red nearby galaxies will not be sampled adequately. If the Mobasher et al. sample were incomplete for faint  $K$ , this would produce a spuriously low normalization and a spuriously bright  $M^*$ . Mobasher et al. used a  $V/V_{\max}$  test (Schmidt 1968) to assess completeness, but they have a very rich cluster at  $z \simeq 0.04$ , and so this test for completeness is invalid, since it relies on spatial homogeneity. It is also possible that any tendency towards brighter  $L^*$  in clusters might bias their result, although they failed to detect any systematic difference in the luminosity function for ellipticals. An alternative viewpoint is to worry that our  $L^*$  may be too faint because our ‘blank-field’ survey regions were necessarily chosen to be free of extremely bright objects. There are two arguments against this being important: (i) we have the same fainter  $L^*$  in the  $z = 0.2 - 0.4$  bin, where the brightest objects are fainter than the positional references; (ii) luminosity function fitting to the binned data ignoring the existence of empty bright bins gives consistent  $L^*$  values.

Similarly, our results diverge quite markedly from those of the Hawaii group (Cowie et al. 1995). They obtain a total  $M_K^* \simeq -23.4$ , which is claimed not to evolve, and a normalization which changes approximately as  $(1+z)^2$ . The local value of  $\phi^*$  for their data is not quoted, but is approximately  $0.006h^3 \text{ Mpc}^{-3}$ . This difference between our results and those of the Hawaii group is more disturbing, since they have a much larger area than Mobasher et al., and almost twice as many redshifts as we do. On the other hand, their sampling rate declines rapidly with  $K$ : in the region containing most of our data ( $15 < K < 17$ ), we have 103 redshifts, whereas they have 73. The fact that we see a clear increase in  $L^*$  at high redshifts, whereas they do not, is barely consistent with limited statistics.

The difference is clearly in the raw data and *not* in the analysis: we have analysed their dataset using the method outlined in Section 5.3 and obtained identical results to Cowie et al. Much turns on the status of the rare bright galaxies at high redshift. We have 9 objects with  $z > 0.6$ ,  $K < 17$ , whereas the Hawaii group have 5. Either they are missing a few objects, or we have an upward fluctuation. However, note that our method of analysis should be robust with respect to density fluctuations. One might worry about having a single rich cluster in the survey with an atypically bright  $L^*$ , and we do indeed have some kind of enhancement in number at  $z \simeq 0.65$ . However, the galaxies here come from two widely separated fields, and there is only one pair within a proper separation of  $1 h^{-1} \text{ Mpc}$ . It therefore seems implausible that our bright  $L^*$  at  $z > 0.6$  can be biased by density fluctuations. However, a larger sample is clearly required for a definitive answer.

Most odd of all is the large discrepancy in luminosity density at low redshifts between our results and those of the Hawaii group. We note that in their lowest redshift bin,  $0 < z < 0.2$ , Cowie et al. have a rather low normalization for their luminosity function, equivalent to  $\phi^* \simeq 0.006h^3 \text{ Mpc}^{-3}$ . Most workers estimate the local optical  $\phi^*$  to lie in the range  $0.01 - 0.03h^3 \text{ Mpc}^{-3}$  (e.g. Loveday et al.’s (1992) luminosity function analysis); these values are approximately 2–5 times larger. We therefore suspect that the lowest-redshift bin of the Hawaii data may be incomplete. If this is ignored, the difference between our higher-redshift results is not so great, as discussed above.

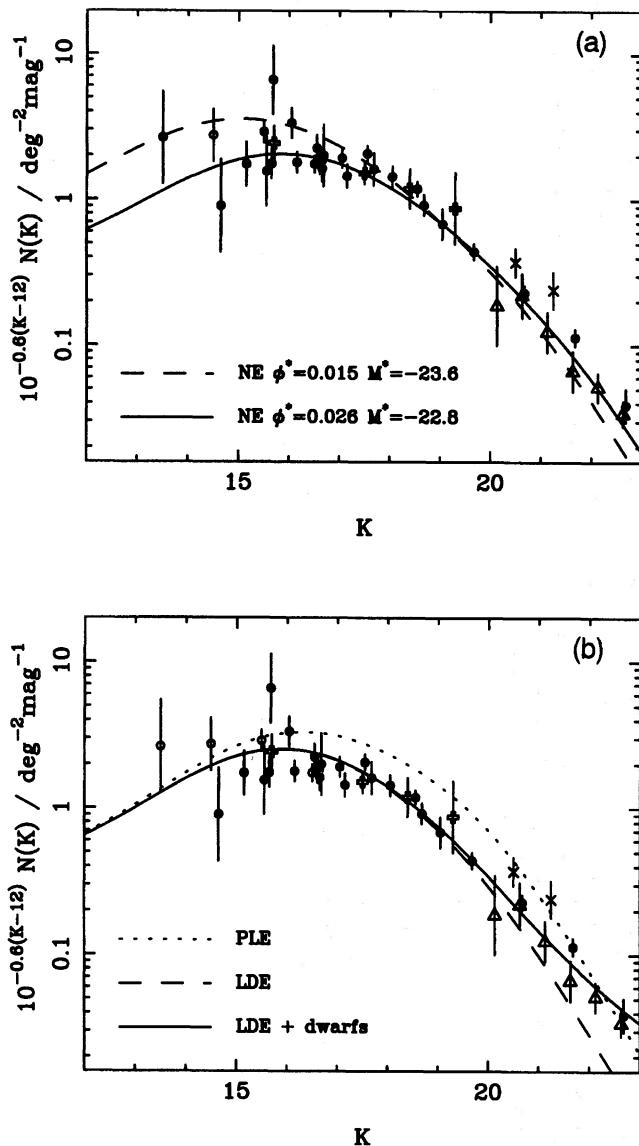
## 6 IMPLICATIONS FOR FAINT COUNTS

The obvious question now is how the models that fit the data at  $K \lesssim 17$  and  $z \lesssim 1$  will fare when extrapolated to fainter  $K$  magnitudes and higher redshifts. Fig. 11 shows the number-count data compared with selected models. The interesting thing here is how well the no-evolution model fits the data, contrary to previous claims. As discussed above, these were made on the basis of analyses which ignored substantial aperture corrections. The counts fall below the Euclidean prediction at about the point where  $M^*$  reaches  $z = 1$ ; since we now have a somewhat fainter  $M^*$ , the turnover moves to fainter magnitudes and matches well the observed decline of the counts. Our increased  $\phi^*$  value means that the overall level of the counts is correctly predicted, as well as the shape. Since our redshift data only rule out the no-evolution model at a moderate level of significance, it seems that this is something that should still be taken seriously. Moving to pure  $L^* \propto 1+z$  luminosity evolution with the same local normalization the predicted counts now significantly exceed the faint data, whereas with the lower normalization it gave a good match. However, conserving luminosity density by scaling  $\phi^* \propto (1+z)^{-1}$  at high redshifts restores the good fit at most magnitudes. The predicted numbers are too small at  $K > 21$ , but this should not be very surprising, since the typical luminosities of galaxies at that level are fainter than we have been able to probe in our luminosity function determination. One simple possibility is that the luminosity function has an extra dwarf component which makes it steeper at the faint end; several authors have argued for such a component both in cluster luminosity functions (e.g. Driver et al. 1994) and in the field (e.g. Gronwall & Koo 1995). Driver et al. obtain the following parameters for the dwarf luminosity function:

$$\begin{aligned} M_{\text{dwarf}}^* &= M_{\text{normal}}^* + 3.5, \\ \phi_{\text{dwarf}}^* &= 2\phi_{\text{normal}}^*, \\ \alpha_{\text{dwarf}} &= -1.8. \end{aligned} \tag{16}$$

Adding such a (non-evolving) low-luminosity contribution to our antimergering normal luminosity function leads to a fit of the faint counts with no adjustment of parameters. We therefore suggest that this combination be regarded as a ‘standard model’ for the infrared luminosity function.

Can these possibilities be constrained by fainter redshift data? Cowie et al. (1994) have described redshift surveys as faint as  $K(6 \text{ arcsec}) = 20$ , and shown that the median redshift continues to follow their no-evolution prediction down to  $K(6 \text{ arcsec}) = 18 - 19$  ( $z_{\text{med}} = 0.65 \pm 0.15$ ), but diverges at  $K(6 \text{ arcsec}) = 19 - 20$  ( $z_{\text{med}} = 0.5 \pm 0.2$ ). Our predictions for these median redshifts are 0.70 and 0.97 respectively for the no-evolution model, 0.87 and 1.17 respectively for the luminosity/density evolution model, and 0.84 and 1.02 respectively for the luminosity/density evolution model with extra dwarfs. The departure from all these models in Cowie et al.’s faint  $K = 19-20$  bin is rather severe. In the context of the model that includes dwarfs, we note that Cowie et al.’s data do contain the suggestion of a low-luminosity clump around  $K = 19.5 - 20$ ,  $z \simeq 0.2$ , which is where the dwarf population would first manifest itself. However, more redshift data at these faint magnitudes are really required for a definite statement: the true median redshift in Cowie et al.’s faintest



**Figure 11.** The K-band number counts, normalized to the usual Euclidean slope. The plotting symbols have the same meanings as in Fig. 5. The various solid lines show different models based on our low-redshift luminosity function results, all assuming  $\Omega = 1$ . Panel (a) shows that no evolution fits the data rather well, in contrast to our earlier predictions based on a brighter  $L^*$  and lower  $\phi^*$ . Panel (b) shows that pure luminosity evolution exceeds the faint counts. Luminosity evolution with declining normalization at high redshift fits better, but the predicted counts are too low in the faintest bins. Including a (non-evolving) dwarf component to the local LF as in Driver et al. (1994) provides a good fit.

bin may well be higher than the figure they estimate from a set of 22 galaxies, of which 9 have redshifts estimated from colours.

## 7 CONCLUSIONS

We have presented an unbiased infrared-selected redshift survey of 124 galaxies to  $K = 17.25$  and deduced the evolution of the K-band luminosity function. Our principal conclusions are the following.

(i) The local normalization of the luminosity function is somewhat higher than has been found in previous work:  $\phi^* = 0.026 \pm 0.003 h^3 \text{ Mpc}^{-3}$ .

(ii) Combined with a slightly fainter  $L^*$  than previous work, we find that an  $\Omega = 1$  model with no evolution fits the number counts rather well to  $K = 21$ .

(iii) However, our data indicate that  $L^*$  is brighter at high redshift, by at least 0.5 mag at  $z = 0.7$ .

(iv) Positive luminosity evolution in this sense then fits the counts only if (a) there is corresponding negative density evolution and (b) there is an additional dwarf component at very low luminosities.

How do we relate these results to optical studies of the galaxy population? We are unable to say much about the ‘faint blue galaxies’ that dominate the faint optical counts: given their colours, we would expect them to have  $M_K \sim -21.5$ , and at  $K < 17.25$  we would not be able to see them beyond  $z > 0.15$ . Rather, they would not manifest themselves until  $K = 19$ – $20$ , and so this suggests an obvious connection between the faint excess in the blue counts and the possible dwarf population discussed above. Such an idea is given further support by the results of Glazebrook et al. (1995b), based on *HST* imaging of random galaxy fields. They find counts of morphologically normal ellipticals and spirals to be much as expected from no-evolution models, whereas the faint excess arises from steep number counts in the irregular population.

Nevertheless, because we favour a model in which the normalization is high, this does have implications for evolution in the optical. Various workers (e.g. Metcalfe et al. 1991, 1995) have argued for a high normalization, based on the good fit of a no-evolution model around  $b_1 = 19$ . This would then imply that the bright counts are incomplete, by a factor of 2 at  $b_1 = 17$ , favouring a prosaic explanation such as that of McGaugh (1994). In this sense, the implication of our result is that the faint blue galaxies may be less dominant than often supposed, and less in need of radical explanations.

Turning to the infrared luminosity function, what are the physical implications of the evolution we have detected? Our results stand in direct contradiction to the simple scaling merger model of BEG, and imply that at least the most luminous galaxies may have had a relatively uneventful history. The amount of luminosity evolution we see is consistent with what is inevitably expected from passive ageing of stellar populations – a point stressed by Cowie et al. (1995). The evolution of the bright end is also similar to that seen in 3CR radio ellipticals by Lilly & Longair (1984) – although see Dunlop & Peacock (1993) for evidence that the infrared light in 3CR galaxies probably has an AGN-related component.

The bright end of the luminosity function is therefore consistent with a picture in which massive spheroids were in place at  $z \gtrsim 1$  and have subsequently evolved passively (see e.g. Bower, Lucey & Ellis 1992 for other pieces of evidence in favour of this conclusion). However, we do not see a luminosity density that declines with time, as expected from passive ageing alone. A possible interpretation of this fact is that additional star formation at intermediate redshifts enhances the luminosity function of lower-luminosity galaxies. In a picture where spheroids are old and passively evolving, it would be natural to associate this feature with the epoch of disc formation (e.g. Gunn 1982). The failure of this process to affect the bright end of the luminosity function would

then be related naturally to morphological segregation and the preference of the most luminous ellipticals for dense environments.

Clearly, this is only a preliminary and qualitative picture, which requires further testing and refinement. Of particular interest will be the evolution at  $z > 1$ , which is rather poorly constrained by existing data. This remains an outstanding task for the new generation of large telescopes.

## ACKNOWLEDGMENTS

We acknowledge the generous allocations of telescope time on the UK Infrared Telescope, operated by the Royal Observatory Edinburgh, the Isaac Newton Telescope, operated by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias, and the Anglo-Australian Telescope. We also thank the staff and telescope operators of these telescopes for their enthusiasm and competent support. The photographic photometry was performed on plates supplied by the UK Schmidt Telescope Unit using the COSMOS measuring machine at the Royal Observatory Edinburgh. The computing and data reduction was carried out on STARLINK which is funded by PPARC. Special thanks go to James Dunlop for allowing us to use his software to compute the K-corrections from galaxy templates, and to Len Cowie for an electronic version of the Hawaii data. KGB acknowledges the support of a SERC research studentship.

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## APPENDIX: THE SPECTROSCOPIC SAMPLE

This appendix presents details of our galaxy sample, listed in Table A1. The ID numbers correspond to those in table 4 of Paper I. Note that, owing to an error, not all of table 4 was printed in Paper I; details of the omitted objects are available on request from the authors.

The spectral type is denoted by a simple nomenclature where 'E' and 'A' respectively refer to whether the spectra have emission (predominantly [O II], H $\beta$  and [O III]) and absorption features (H + K, G, H $\beta$ -H $\delta$ ). Additionally we use 'ER' to refer to spectra with strong H $\alpha$  emission where observable. A selection of the survey spectra is shown in Fig. A1.

We give photometry both within 4-arcsec diameter apertures, as in Paper I, and within 20  $h^{-1}$  kpc metric apertures. For about 10 per cent of our objects, we were unable to measure a big enough aperture at low redshift or small enough at high redshift to reach 20  $h^{-1}$  kpc. For these objects we extrapolate with the  $r^{0.4}$  growth law – typically the extrapolations are over a small range, 20–50 per cent of the diameter, and thus deviations from the  $r^{0.4}$  law will be only at the  $\ll 0.1$  mag level.

The last two columns give weights for incompleteness as a function of  $K$  and colour. The former was obtained by the ratio of the raw number counts in the sample to the mean count expected over 552 arcmin<sup>2</sup>. The latter was obtained by dividing the  $(R - K) - K$  colour-magnitude plane into cells (using increments of 0.3 in  $K$  and 0.5 in  $R - K$ ) and comparing the populations of these cells in our total and spectroscopic samples. A colour-dependent weight was then deduced, normalized to a mean of unity at each  $K$ . Where cell populations were too low for meaningful statistics, a weight of unity was assumed.

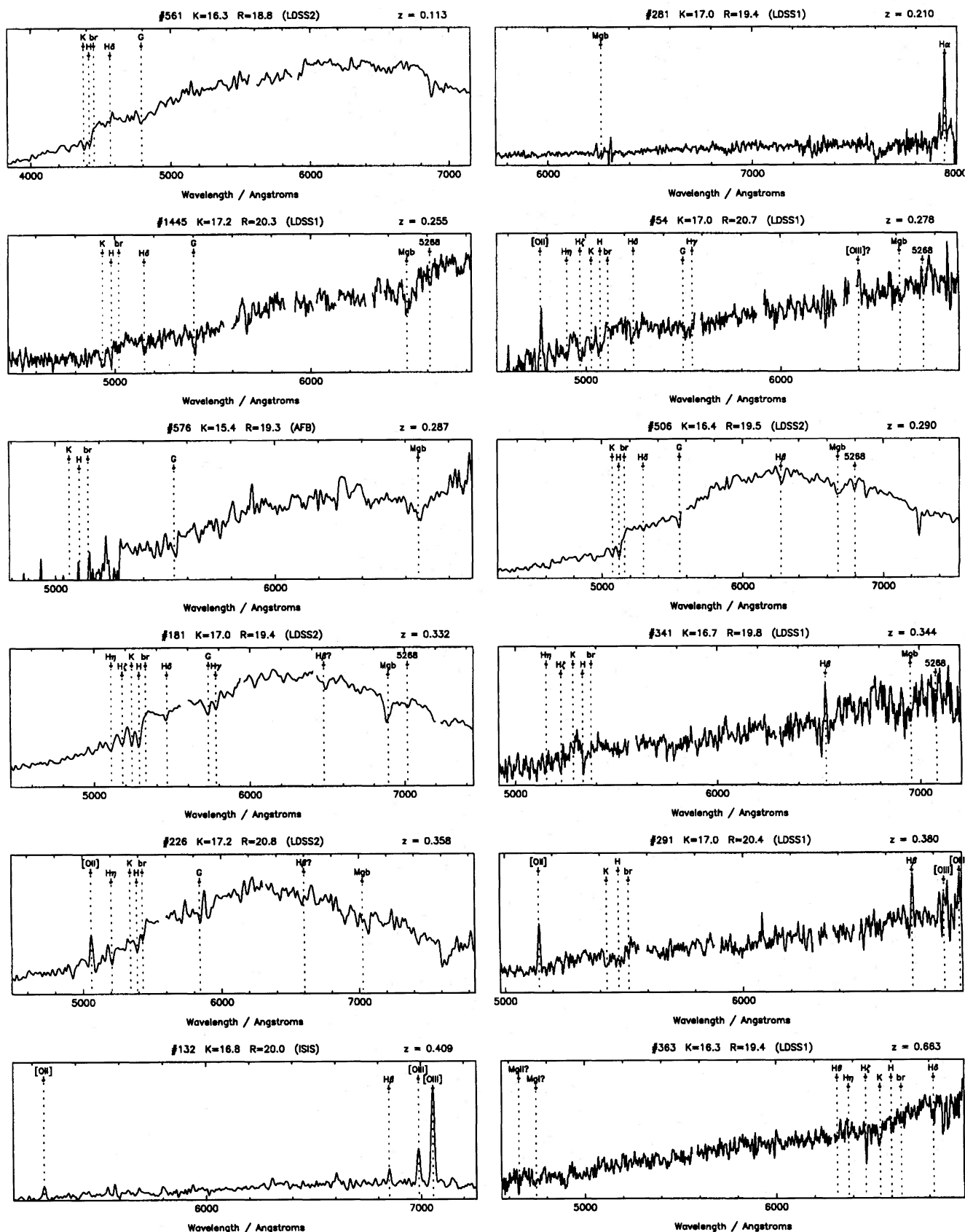


Figure A1. Plots of a random selection of spectra from the survey. The positions of standard spectral features are indicated for the adopted redshift.

**Table A1.** The K-selected spectroscopic sample.

| ID  | RA (1950.0) | DEC          | <i>z</i> | Ty | <i>K</i> (4 arcsec) | <i>K</i> (20 <i>h</i> <sup>-1</sup> kpc) | <i>R</i> (4 arcsec) | <i>R</i> (20 <i>h</i> <sup>-1</sup> kpc) | <i>w</i> ( <i>K</i> ) | <i>w</i> ( <i>R</i> − <i>K</i> ) |
|-----|-------------|--------------|----------|----|---------------------|------------------------------------------|---------------------|------------------------------------------|-----------------------|----------------------------------|
| 11  | 22 38 59.55 | +00 37 38.27 | 0.129    | A  | 14.25 ± 0.05        | 13.78 ± 0.05                             | 17.84 ± 0.04        | 17.05 ± 0.03                             | 0.24                  | 1.00                             |
| 18  | 22 38 41.69 | +00 31 49.68 | 0.384    | A  | 16.43 ± 0.10        | 16.44 ± 0.16                             | 20.39 ± 0.05        | 20.08 ± 0.04                             | 3.93                  | 0.81                             |
| 24  | 22 38 37.94 | +00 33 18.39 | 0.075    | E  | 16.08 ± 0.11        | 15.42 ± 0.12                             | 18.48 ± 0.04        | 17.58 ± 0.03                             | 2.64                  | 1.00                             |
| 31  | 22 38 43.84 | +00 33 55.83 | 0.666    | A  | 15.90 ± 0.09        | 15.75 ± 0.12                             | 20.20 ± 0.05        | 20.13 ± 0.04                             | 2.09                  | 1.00                             |
| 54  | 22 38 38.45 | +00 34 51.21 | 0.278    | EA | 16.96 ± 0.17        | 16.65 ± 0.21                             | 20.68 ± 0.06        | 20.15 ± 0.05                             | 3.17                  | 1.33                             |
| 56  | 22 38 34.54 | +00 35 28.69 | 0.278    | EA | 16.74 ± 0.15        | 16.35 ± 0.19                             | 19.87 ± 0.05        | 19.48 ± 0.04                             | 2.69                  | 0.98                             |
| 66  | 22 40 30.26 | +00 25 56.63 | 0.399    | EA | 16.92 ± 0.18        | 16.65 ± 0.22                             | 20.79 ± 0.05        | 20.52 ± 0.04                             | 3.17                  | 1.29                             |
| 68  | 22 40 31.98 | +00 26 12.71 | 0.147    | EA | 16.25 ± 0.10        | 15.97 ± 0.18                             | 19.00 ± 0.04        | 17.92 ± 0.03                             | 2.64                  | 1.00                             |
| 73  | 22 40 27.78 | +00 27 11.34 | 0.148    | A  | 15.48 ± 0.07        | 15.46 ± 0.14                             | 18.67 ± 0.04        | 18.55 ± 0.03                             | 0.91                  | 0.98                             |
| 77  | 22 40 02.69 | +00 21 34.23 | 0.160    | A  | 16.31 ± 0.12        | 15.88 ± 0.16                             | 19.70 ± 0.04        | 19.18 ± 0.03                             | 3.93                  | 1.21                             |
| 90  | 22 40 12.72 | +00 21 29.73 | 0.302    | A  | 16.84 ± 0.18        | 16.88 ± 0.20                             | 18.22 ± 0.04        | 18.24 ± 0.03                             | 3.17                  | 1.00                             |
| 91  | 22 40 09.02 | +00 21 37.83 | 0.191    | A  | 15.83 ± 0.09        | 15.54 ± 0.14                             | 19.00 ± 0.04        | 18.34 ± 0.03                             | 2.09                  | 1.00                             |
| 95  | 22 40 11.48 | +00 22 26.00 | 0.289    | A  | 16.33 ± 0.12        | 16.44 ± 0.18                             | 19.85 ± 0.04        | 19.68 ± 0.03                             | 3.93                  | 0.79                             |
| 96  | 22 40 13.93 | +00 22 32.01 | 0.225    | E  | 16.04 ± 0.10        | 15.98 ± 0.15                             | 21.81 ± 0.10        | 21.63 ± 0.09                             | 2.64                  | 1.00                             |
| 104 | 22 40 18.20 | +00 24 30.77 | 0.654    | A  | 17.14 ± 0.20        | 16.84 ± 0.24                             | 22.07 ± 0.11        | 21.77 ± 0.09                             | 8.91                  | 1.00                             |
| 106 | 22 40 18.74 | +00 24 58.85 | 0.801    | A  | 16.22 ± 0.10        | 16.16 ± 0.10                             | 21.70 ± 0.09        | 21.63 ± 0.06                             | 2.64                  | 1.00                             |
| 109 | 22 40 20.59 | +00 25 39.50 | 0.148    | EA | 15.42 ± 0.06        | 14.96 ± 0.08                             | 19.38 ± 0.04        | 18.76 ± 0.03                             | 0.91                  | 0.86                             |
| 118 | 22 40 15.23 | +00 30 04.37 | 0.654    | A  | 16.67 ± 0.15        | 16.71 ± 0.14                             | 21.33 ± 0.07        | 21.18 ± 0.05                             | 2.69                  | 0.86                             |
| 120 | 22 40 19.71 | +00 30 14.37 | 0.210    | A  | 15.69 ± 0.08        | 15.51 ± 0.12                             | 19.00 ± 0.05        | 18.42 ± 0.04                             | 0.83                  | 0.98                             |
| 121 | 22 40 16.51 | +00 30 18.37 | 0.582    | A  | 15.95 ± 0.09        | 15.96 ± 0.08                             | 19.95 ± 0.04        | 19.64 ± 0.03                             | 2.09                  | 1.00                             |
| 132 | 22 39 58.28 | +00 24 46.24 | 0.409    | E  | 16.82 ± 0.15        | 16.68 ± 0.19                             | 20.04 ± 0.05        | 19.88 ± 0.04                             | 3.17                  | 0.98                             |
| 138 | 22 39 37.84 | +00 21 26.98 | 0.271    | EA | 16.11 ± 0.10        | 15.91 ± 0.13                             | 20.12 ± 0.05        | 19.53 ± 0.04                             | 2.64                  | 1.00                             |
| 146 | 22 39 38.01 | +00 21 50.51 | 0.291    | EA | 16.75 ± 0.15        | 16.58 ± 0.20                             | 19.93 ± 0.05        | 19.34 ± 0.03                             | 2.69                  | 0.98                             |
| 149 | 22 39 33.89 | +00 22 29.13 | 0.074    | ER | 15.03 ± 0.06        | 14.47 ± 0.11                             | No Data             | No Data                                  | 0.63                  | 1.00                             |
| 151 | 22 39 40.14 | +00 24 16.61 | 0.153    | EA | 15.56 ± 0.07        | 15.55 ± 0.14                             | 18.49 ± 0.04        | 17.82 ± 0.03                             | 0.83                  | 1.02                             |
| 159 | 22 39 37.16 | +00 25 44.39 | 0.073    | A  | 13.30 ± 0.05        | 12.67 ± 0.05                             | 16.28 ± 0.04        | 15.10 ± 0.03                             | 1.00                  | 1.00                             |
| 164 | 22 39 38.59 | +00 28 33.25 | 0.408    | EA | 16.88 ± 0.17        | 16.51 ± 0.15                             | 20.95 ± 0.16        | 20.72 ± 0.13                             | 3.17                  | 1.00                             |
| 169 | 22 39 32.42 | +00 31 27.18 | 0.150    | A  | 15.73 ± 0.10        | 15.31 ± 0.10                             | 18.94 ± 0.04        | 18.30 ± 0.03                             | 0.83                  | 0.98                             |
| 173 | 22 39 34.22 | +00 31 53.23 | 0.127    | A  | 15.39 ± 0.09        | 14.52 ± 0.07                             | 18.48 ± 0.04        | 17.31 ± 0.03                             | 0.91                  | 1.29                             |
| 181 | 22 39 31.48 | +00 25 00.98 | 0.332    | EA | 16.98 ± 0.18        | 16.47 ± 0.21                             | 19.43 ± 0.04        | 18.92 ± 0.03                             | 3.17                  | 1.00                             |
| 190 | 22 39 05.99 | +00 22 58.60 | 0.387    | A  | 15.93 ± 0.09        | 15.95 ± 0.12                             | 19.82 ± 0.04        | 19.67 ± 0.03                             | 2.09                  | 1.00                             |
| 198 | 22 38 55.21 | +00 24 03.35 | 0.290    | A  | 16.00 ± 0.09        | 15.81 ± 0.10                             | 19.31 ± 0.04        | 18.83 ± 0.03                             | 2.09                  | 1.00                             |
| 199 | 22 38 56.90 | +00 24 14.64 | 0.388    | EA | 16.89 ± 0.17        | 16.88 ± 0.21                             | 20.54 ± 0.05        | 20.24 ± 0.04                             | 3.17                  | 1.29                             |
| 212 | 22 39 00.35 | +00 29 45.16 | 0.179    | EA | 16.91 ± 0.18        | 16.50 ± 0.21                             | 20.13 ± 0.07        | 19.47 ± 0.06                             | 3.17                  | 0.98                             |
| 220 | 22 38 47.57 | +00 26 21.46 | 0.777    | A  | 16.78 ± 0.15        | 16.67 ± 0.15                             | 21.50 ± 0.08        | 21.37 ± 0.07                             | 3.17                  | 0.86                             |
| 224 | 22 38 39.84 | +00 26 19.33 | 0.063    | A  | 16.20 ± 0.11        | 15.79 ± 0.15                             | 20.01 ± 0.04        | 19.48 ± 0.05                             | 2.64                  | 0.79                             |
| 226 | 22 38 39.41 | +00 26 32.98 | 0.358    | EA | 17.15 ± 0.20        | 16.77 ± 0.22                             | 20.80 ± 0.06        | 20.42 ± 0.04                             | 8.91                  | 1.33                             |
| 229 | 22 38 39.37 | +00 27 32.27 | 0.503    | A  | 16.62 ± 0.13        | 16.39 ± 0.15                             | 20.33 ± 0.05        | 19.76 ± 0.05                             | 2.69                  | 0.81                             |
| 244 | 22 38 37.48 | +00 29 50.20 | 0.442    | A  | 16.61 ± 0.18        | 16.34 ± 0.21                             | 20.29 ± 0.05        | 20.02 ± 0.03                             | 2.69                  | 0.81                             |
| 250 | 22 38 53.87 | +00 20 58.55 | 0.658    | E  | 16.52 ± 0.17        | 16.41 ± 0.22                             | 22.22 ± 0.12        | 22.15 ± 0.09                             | 2.69                  | 1.00                             |
| 253 | 22 39 03.52 | +00 22 30.43 | 0.301    | A  | 15.13 ± 0.07        | 15.09 ± 0.09                             | 18.85 ± 0.04        | 18.60 ± 0.03                             | 0.63                  | 1.00                             |
| 259 | 22 38 50.30 | +00 29 11.81 | 0.276    | EA | 16.20 ± 0.14        | 16.05 ± 0.21                             | 19.72 ± 0.05        | 19.22 ± 0.03                             | 2.64                  | 0.79                             |
| 265 | 00 52 10.66 | +00 15 35.34 | 0.207    | A  | 14.73 ± 0.05        | 14.22 ± 0.06                             | 18.03 ± 0.04        | 17.45 ± 0.03                             | 1.26                  | 1.00                             |
| 267 | 00 52 06.99 | +00 15 54.34 | 0.205    | A  | 15.80 ± 0.08        | 15.49 ± 0.12                             | 18.79 ± 0.04        | 18.34 ± 0.03                             | 2.09                  | 1.00                             |
| 281 | 00 52 29.84 | +00 16 48.97 | 0.210    | ER | 16.97 ± 0.16        | 16.63 ± 0.22                             | 19.42 ± 0.04        | 19.08 ± 0.03                             | 3.17                  | 1.00                             |
| 285 | 00 52 34.76 | +00 20 19.43 | 0.067    | E  | 15.56 ± 0.08        | 15.01 ± 0.13                             | 18.14 ± 0.04        | 17.39 ± 0.03                             | 0.83                  | 1.02                             |
| 288 | 00 52 37.75 | +00 15 38.02 | 0.146    | ER | 15.57 ± 0.07        | 14.97 ± 0.10                             | 18.60 ± 0.04        | 17.62 ± 0.03                             | 0.83                  | 0.98                             |
| 291 | 00 52 13.80 | +00 23 32.68 | 0.380    | E  | 16.96 ± 0.20        | 16.82 ± 0.20                             | 20.36 ± 0.05        | 20.16 ± 0.04                             | 3.17                  | 0.67                             |
| 293 | 00 52 15.23 | +00 23 49.49 | 0.377    | A  | 15.52 ± 0.08        | 15.28 ± 0.07                             | 18.76 ± 0.04        | 18.50 ± 0.03                             | 0.83                  | 0.98                             |
| 295 | 00 52 14.31 | +00 23 56.77 | 0.236    | A  | 15.36 ± 0.07        | 14.95 ± 0.07                             | 18.42 ± 0.04        | 18.00 ± 0.03                             | 0.91                  | 1.29                             |

Table A1 – continued

| ID  | RA          | (1950.0)     | DEC   | z  | Ty           | K(4 arcsec)  | K(20 h <sup>-1</sup> kpc) | R(4 arcsec)  | R(20 h <sup>-1</sup> kpc) | w(K) | w(R − K) |
|-----|-------------|--------------|-------|----|--------------|--------------|---------------------------|--------------|---------------------------|------|----------|
| 297 | 00 52 04.75 | +00 20 52.75 | 0.067 | ER | 15.43 ± 0.07 | 14.16 ± 0.08 | 18.05 ± 0.04              | 16.01 ± 0.03 | 0.91                      | 0.86 |          |
| 300 | 00 52 09.76 | +00 21 30.25 | 0.087 | EA | 16.04 ± 0.09 | 15.09 ± 0.11 | 18.34 ± 0.04              | 16.91 ± 0.03 | 2.64                      | 1.00 |          |
| 302 | 00 52 08.35 | +00 21 48.30 | 0.086 | E  | 14.18 ± 0.05 | 13.48 ± 0.06 | 16.95 ± 0.04              | 16.02 ± 0.03 | 0.37                      | 1.00 |          |
| 312 | 00 52 20.15 | +00 24 14.74 | 0.236 | A  | 14.97 ± 0.06 | 14.77 ± 0.06 | 18.51 ± 0.04              | 18.12 ± 0.03 | 1.87                      | 1.00 |          |
| 313 | 00 52 17.60 | +00 24 20.68 | 0.235 | A  | 16.25 ± 0.10 | 16.07 ± 0.18 | 19.63 ± 0.05              | 19.30 ± 0.04 | 2.64                      | 1.21 |          |
| 314 | 00 52 21.87 | +00 24 29.16 | 0.471 | A  | 17.02 ± 0.18 | 16.82 ± 0.22 | 20.06 ± 0.05              | 19.86 ± 0.04 | 8.91                      | 0.67 |          |
| 316 | 00 52 25.49 | +00 20 11.44 | 0.676 | A  | 16.80 ± 0.13 | 16.71 ± 0.18 | 21.50 ± 0.09              | 21.42 ± 0.07 | 3.17                      | 0.86 |          |
| 317 | 00 52 24.21 | +00 20 29.08 | 0.124 | A  | 15.20 ± 0.06 | 14.89 ± 0.07 | 17.94 ± 0.04              | 17.51 ± 0.03 | 0.63                      | 0.86 |          |
| 319 | 00 52 25.52 | +00 20 39.10 | 0.546 | EA | 16.92 ± 0.16 | 16.79 ± 0.21 | 20.41 ± 0.06              | 20.28 ± 0.05 | 3.17                      | 0.98 |          |
| 320 | 00 52 24.81 | +00 20 45.78 | 0.124 | E  | 16.63 ± 0.12 | 16.09 ± 0.20 | 18.79 ± 0.04              | 17.67 ± 0.03 | 2.69                      | 1.00 |          |
| 321 | 00 52 16.03 | +00 18 58.77 | 0.217 | EA | 16.50 ± 0.13 | 16.48 ± 0.21 | 20.14 ± 0.05              | 19.98 ± 0.04 | 3.93                      | 0.81 |          |
| 323 | 00 52 17.10 | +00 19 55.94 | 0.321 | E  | 16.93 ± 0.17 | 16.49 ± 0.21 | 19.20 ± 0.04              | 18.60 ± 0.03 | 3.17                      | 0.86 |          |
| 329 | 00 52 27.57 | +00 21 23.25 | 0.153 | A  | 15.75 ± 0.10 | 15.53 ± 0.18 | 19.33 ± 0.04              | 18.81 ± 0.03 | 0.83                      | 1.00 |          |
| 333 | 00 52 46.55 | +00 10 49.16 | 0.417 | A  | 16.86 ± 0.17 | 16.64 ± 0.19 | 20.65 ± 0.05              | 20.59 ± 0.04 | 3.17                      | 1.29 |          |
| 334 | 00 52 47.79 | +00 10 52.72 | 0.192 | A  | 15.83 ± 0.08 | 15.62 ± 0.12 | 19.80 ± 0.04              | 18.48 ± 0.03 | 2.09                      | 1.00 |          |
| 336 | 00 52 48.07 | +00 11 11.93 | 0.193 | EA | 16.57 ± 0.13 | 16.48 ± 0.18 | 19.99 ± 0.04              | 19.63 ± 0.03 | 2.69                      | 1.19 |          |
| 337 | 00 52 48.86 | +00 11 18.85 | 0.577 | A  | 16.38 ± 0.12 | 16.27 ± 0.11 | 19.53 ± 0.04              | 19.37 ± 0.03 | 3.93                      | 1.19 |          |
| 340 | 00 52 48.71 | +00 11 51.46 | 0.636 | A  | 15.59 ± 0.07 | 15.47 ± 0.07 | 19.86 ± 0.04              | 19.71 ± 0.03 | 0.83                      | 1.00 |          |
| 341 | 00 52 42.98 | +00 12 12.43 | 0.344 | EA | 16.66 ± 0.14 | 16.43 ± 0.14 | 19.82 ± 0.04              | 19.57 ± 0.03 | 2.69                      | 0.98 |          |
| 346 | 00 53 10.28 | +00 10 42.10 | 0.102 | A  | 16.59 ± 0.13 | 15.69 ± 0.18 | 20.06 ± 0.05              | 19.38 ± 0.06 | 2.69                      | 1.19 |          |
| 349 | 00 53 11.74 | +00 11 38.97 | 0.154 | EA | 16.56 ± 0.12 | 15.96 ± 0.13 | 19.13 ± 0.04              | 18.05 ± 0.03 | 2.69                      | 1.00 |          |
| 354 | 00 53 12.64 | +00 05 48.91 | 0.153 | A  | 14.29 ± 0.05 | 13.66 ± 0.05 | 17.80 ± 0.04              | 17.00 ± 0.03 | 0.24                      | 1.00 |          |
| 355 | 00 53 08.76 | +00 05 55.12 | 0.071 | E  | 16.68 ± 0.15 | 16.21 ± 0.17 | 18.88 ± 0.04              | 18.41 ± 0.03 | 2.69                      | 0.86 |          |
| 356 | 00 53 09.54 | +00 06 05.00 | 0.209 | A  | 15.08 ± 0.06 | 14.84 ± 0.08 | 18.27 ± 0.04              | 17.87 ± 0.03 | 0.63                      | 1.00 |          |
| 358 | 00 53 16.43 | +00 06 08.82 | 0.495 | A  | 16.15 ± 0.10 | 15.95 ± 0.09 | 19.73 ± 0.04              | 19.50 ± 0.03 | 2.64                      | 0.79 |          |
| 360 | 00 52 48.99 | +00 09 26.06 | 0.673 | A  | 17.24 ± 0.21 | 17.20 ± 0.27 | 22.00 ± 0.11              | 21.96 ± 0.08 | 8.91                      | 1.00 |          |
| 362 | 00 52 47.71 | +00 09 43.32 | 0.505 | EA | 17.10 ± 0.18 | 17.11 ± 0.20 | 20.18 ± 0.04              | 20.09 ± 0.03 | 8.91                      | 0.67 |          |
| 363 | 00 52 46.35 | +00 10 04.23 | 0.663 | A  | 16.32 ± 0.10 | 15.96 ± 0.08 | 19.36 ± 0.04              | 18.92 ± 0.03 | 3.93                      | 1.21 |          |
| 364 | 00 52 47.10 | +00 10 19.78 | 0.431 | A  | 16.58 ± 0.12 | 16.46 ± 0.13 | 20.14 ± 0.04              | 19.92 ± 0.03 | 2.69                      | 0.81 |          |
| 374 | 00 52 51.40 | +00 05 29.65 | 0.044 | EA | 16.92 ± 0.18 | 15.69 ± 0.20 | 19.04 ± 0.04              | 17.53 ± 0.03 | 3.17                      | 0.86 |          |
| 378 | 00 52 51.47 | +00 07 28.52 | 0.113 | EA | 17.10 ± 0.20 | 16.21 ± 0.19 | 19.70 ± 0.04              | 18.81 ± 0.03 | 8.91                      | 1.00 |          |
| 380 | 00 52 52.22 | +00 07 45.79 | 0.734 | A  | 17.19 ± 0.20 | 17.06 ± 0.32 | 22.65 ± 0.19              | 22.52 ± 0.18 | 8.91                      | 1.00 |          |
| 385 | 00 52 59.56 | +00 09 44.62 | 0.045 | A  | 14.35 ± 0.05 | 12.70 ± 0.05 | 16.82 ± 0.04              | 15.14 ± 0.03 | 0.24                      | 1.00 |          |
| 387 | 00 53 02.15 | +00 09 46.91 | 0.675 | A  | 16.88 ± 0.16 | 16.71 ± 0.26 | 20.85 ± 0.13              | 20.68 ± 0.13 | 3.17                      | 1.29 |          |
| 392 | 00 53 07.44 | +00 07 15.48 | 0.153 | EA | 16.24 ± 0.10 | 16.12 ± 0.15 | 20.18 ± 0.05              | 19.79 ± 0.04 | 2.64                      | 0.79 |          |
| 400 | 00 53 11.97 | +00 13 25.19 | 0.192 | A  | 17.21 ± 0.19 | 16.81 ± 0.26 | 20.46 ± 0.06              | 20.06 ± 0.06 | 8.91                      | 0.67 |          |
| 405 | 01 53 01.29 | +00 41 51.41 | 0.080 | ER | 15.73 ± 0.09 | 15.04 ± 0.09 | 18.50 ± 0.04              | 17.19 ± 0.03 | 0.83                      | 1.02 |          |
| 406 | 01 53 05.36 | +00 42 32.46 | 0.121 | A  | 14.28 ± 0.05 | 13.78 ± 0.07 | 18.18 ± 0.04              | 17.10 ± 0.03 | 0.24                      | 1.00 |          |
| 411 | 01 53 28.63 | +00 46 32.36 | 0.085 | A  | 14.43 ± 0.06 | 13.86 ± 0.07 | 17.39 ± 0.04              | 16.73 ± 0.03 | 0.24                      | 1.00 |          |
| 418 | 01 53 31.84 | +00 45 49.69 | 0.079 | A  | 15.05 ± 0.07 | 14.53 ± 0.10 | 17.74 ± 0.04              | 17.13 ± 0.03 | 0.63                      | 1.00 |          |
| 422 | 01 53 21.37 | +00 46 21.86 | 0.113 | A  | 15.66 ± 0.07 | 15.48 ± 0.10 | 19.15 ± 0.04              | 18.94 ± 0.04 | 0.83                      | 0.98 |          |
| 423 | 01 53 20.49 | +00 46 52.46 | 0.080 | A  | 15.27 ± 0.06 | 14.88 ± 0.19 | 17.95 ± 0.04              | 17.37 ± 0.03 | 0.91                      | 0.86 |          |
| 425 | 01 53 24.68 | +00 44 39.93 | 0.080 | A  | 14.68 ± 0.05 | 13.76 ± 0.07 | 17.51 ± 0.04              | 16.44 ± 0.03 | 1.26                      | 1.00 |          |
| 431 | 01 53 21.72 | +00 41 17.11 | 0.076 | ER | 15.67 ± 0.09 | 15.11 ± 0.21 | 18.13 ± 0.04              | 16.76 ± 0.03 | 0.83                      | 1.00 |          |
| 432 | 01 53 20.86 | +00 41 57.87 | 0.080 | ER | 15.42 ± 0.08 | 14.67 ± 0.09 | 18.04 ± 0.04              | 17.19 ± 0.03 | 0.91                      | 0.86 |          |
| 434 | 01 53 31.18 | +00 43 20.30 | 0.080 | A  | 14.23 ± 0.05 | 13.91 ± 0.06 | 17.25 ± 0.04              | 16.77 ± 0.03 | 0.37                      | 1.00 |          |
| 454 | 01 53 13.88 | +00 43 58.12 | 0.376 | A  | 16.82 ± 0.13 | 16.66 ± 0.21 | 20.28 ± 0.05              | 20.17 ± 0.04 | 3.17                      | 0.98 |          |
| 455 | 01 53 13.50 | +00 44 41.53 | 0.206 | A  | 15.77 ± 0.07 | 15.60 ± 0.11 | 18.77 ± 0.04              | 18.65 ± 0.03 | 2.09                      | 1.00 |          |
| 457 | 01 53 14.85 | +00 45 01.44 | 0.551 | A  | 17.10 ± 0.17 | 16.93 ± 0.27 | 20.83 ± 0.06              | 20.66 ± 0.04 | 8.91                      | 1.33 |          |
| 462 | 01 53 12.42 | +00 40 35.81 | 0.080 | A  | 15.22 ± 0.08 | 14.28 ± 0.10 | 17.95 ± 0.04              | 16.22 ± 0.03 | 0.63                      | 0.86 |          |
| 469 | 01 52 48.85 | +00 39 51.71 | 0.554 | A  | 15.57 ± 0.09 | 15.49 ± 0.10 | 18.50 ± 0.04              | 18.39 ± 0.03 | 0.83                      | 1.02 |          |
| 491 | 01 52 35.55 | +00 36 27.18 | 0.474 | A  | 15.63 ± 0.07 | 15.43 ± 0.08 | 19.34 ± 0.04              | 19.13 ± 0.03 | 0.83                      | 1.00 |          |
| 502 | 01 52 45.28 | +00 22 33.32 | 0.403 | A  | 16.15 ± 0.10 | 15.90 ± 0.11 | 19.93 ± 0.04              | 19.61 ± 0.03 | 2.64                      | 0.79 |          |
| 506 | 01 52 44.12 | +00 23 21.20 | 0.290 | A  | 16.43 ± 0.12 | 16.28 ± 0.10 | 19.46 ± 0.04              | 19.31 ± 0.03 | 3.93                      | 1.19 |          |

**Table A1** – *continued*

| ID   | RA (1950.0) | DEC          | $z$   | Ty | $K(4 \text{ arcsec})$ | $K(20 h^{-1} \text{ kpc})$ | $R(4 \text{ arcsec})$ | $R(20 h^{-1} \text{ kpc})$ | $w(K)$ | $w(R - K)$ |
|------|-------------|--------------|-------|----|-----------------------|----------------------------|-----------------------|----------------------------|--------|------------|
| 510  | 01 52 52.08 | +00 29 46.18 | 0.088 | ER | $15.23 \pm 0.06$      | $14.83 \pm 0.09$           | $17.96 \pm 0.04$      | $17.31 \pm 0.03$           | 0.63   | 0.86       |
| 511  | 01 52 49.82 | +00 29 47.50 | 0.471 | EA | $16.66 \pm 0.12$      | $16.56 \pm 0.20$           | $20.48 \pm 0.05$      | $20.17 \pm 0.03$           | 2.69   | 1.29       |
| 517  | 01 52 45.72 | +00 27 46.09 | 0.131 | ER | $14.85 \pm 0.05$      | $14.40 \pm 0.07$           | $18.22 \pm 0.04$      | $17.51 \pm 0.03$           | 1.87   | 1.00       |
| 520  | 01 52 51.65 | +00 26 07.60 | 0.252 | EA | $16.63 \pm 0.12$      | $16.23 \pm 0.17$           | $20.03 \pm 0.05$      | $19.58 \pm 0.04$           | 2.69   | 1.19       |
| 521  | 01 52 50.02 | +00 26 30.46 | 0.140 | EA | $16.68 \pm 0.12$      | $16.24 \pm 0.21$           | $18.97 \pm 0.04$      | $18.16 \pm 0.03$           | 2.69   | 0.86       |
| 525  | 01 52 55.08 | +00 25 07.90 | 0.339 | EA | $17.00 \pm 0.18$      | $16.77 \pm 0.18$           | $20.19 \pm 0.05$      | $19.97 \pm 0.04$           | 3.17   | 0.67       |
| 540  | 01 52 27.74 | +00 24 32.90 | 0.190 | A  | $15.63 \pm 0.07$      | $15.27 \pm 0.08$           | $18.58 \pm 0.04$      | $17.90 \pm 0.03$           | 0.83   | 1.02       |
| 558  | 01 52 41.29 | +00 28 27.72 | 0.119 | A  | $15.43 \pm 0.07$      | $14.25 \pm 0.07$           | $17.80 \pm 0.04$      | $16.48 \pm 0.03$           | 0.91   | 1.00       |
| 561  | 01 52 39.81 | +00 29 05.68 | 0.113 | A  | $16.27 \pm 0.10$      | $15.43 \pm 0.14$           | $18.78 \pm 0.04$      | $18.07 \pm 0.03$           | 3.93   | 1.00       |
| 563  | 01 52 36.76 | +00 25 14.35 | 0.080 | ER | $14.40 \pm 0.05$      | $13.73 \pm 0.06$           | $18.09 \pm 0.04$      | $16.73 \pm 0.03$           | 0.24   | 1.00       |
| 564  | 01 52 37.05 | +00 25 30.23 | 0.339 | A  | $16.92 \pm 0.16$      | $16.44 \pm 0.21$           | $19.70 \pm 0.04$      | $19.17 \pm 0.03$           | 3.17   | 1.00       |
| 568  | 01 52 24.55 | +00 31 17.28 | 0.156 | A  | $14.38 \pm 0.05$      | $13.99 \pm 0.07$           | $18.04 \pm 0.04$      | $17.56 \pm 0.03$           | 0.24   | 1.00       |
| 571  | 01 52 38.20 | +00 39 55.06 | 0.169 | A  | $15.20 \pm 0.08$      | $14.78 \pm 0.11$           | $18.50 \pm 0.04$      | $18.20 \pm 0.03$           | 0.63   | 1.29       |
| 574  | 01 52 46.01 | +00 32 37.12 | 0.286 | A  | $15.16 \pm 0.06$      | $14.72 \pm 0.07$           | $18.78 \pm 0.04$      | $18.23 \pm 0.03$           | 0.63   | 0.86       |
| 576  | 01 52 44.69 | +00 31 30.01 | 0.287 | A  | $15.42 \pm 0.08$      | $15.34 \pm 0.12$           | $19.32 \pm 0.04$      | $18.48 \pm 0.03$           | 0.91   | 0.86       |
| 1445 | 13 42 05.07 | +00 09 32.74 | 0.255 | A  | $17.19 \pm 0.27$      | $16.89 \pm 0.35$           | $20.30 \pm 0.05$      | $20.00 \pm 0.04$           | 8.91   | 0.67       |
| 1446 | 13 42 08.32 | +00 09 56.45 | 0.370 | A  | $16.45 \pm 0.15$      | $16.24 \pm 0.14$           | $20.52 \pm 0.05$      | $20.31 \pm 0.04$           | 3.93   | 1.00       |
| 1450 | 13 42 05.43 | +00 10 26.78 | 0.430 | E  | $16.68 \pm 0.18$      | $16.50 \pm 0.30$           | $20.54 \pm 0.05$      | $20.36 \pm 0.04$           | 2.69   | 1.29       |
| 1459 | 13 42 03.58 | +00 05 40.13 | 0.408 | EA | $16.50 \pm 0.14$      | $16.31 \pm 0.12$           | $20.15 \pm 0.05$      | $19.96 \pm 0.04$           | 2.69   | 0.81       |
| 1550 | 13 41 54.03 | +00 05 02.38 | 0.088 | A  | $14.19 \pm 0.05$      | $13.64 \pm 0.06$           | $17.01 \pm 0.03$      | $16.18 \pm 0.03$           | 0.37   | 1.00       |

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