New $H$-band galaxy number counts: a large local hole in the galaxy distribution

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ABSTRACT

We examine $H$-band number counts determined using new photometry over two fields with a combined solid angle of 0.30 deg$^2$ to $H \approx 19$, as well as bright data ($H \leq 14$) from the two-Micron All-Sky Survey (2MASS). First, we examine the bright number counts from 2MASS extracted for the $\approx 4000$-deg$^2$ Automated Plate Measuring machine (APM) survey area situated around the southern Galactic pole. We find a deficiency of $\approx 25$ per cent at $H = 13$ with respect to homogeneous predictions, in line with previous results in the $B$ and $K_s$ bands. In addition, we examine the bright counts extracted for $|b| > 20^\circ$ (covering $\approx 27 000$ deg$^2$); we find a relatively constant deficit in the counts of $\approx 15–20$ per cent to $H = 14$. We investigate various possible causes for these results; namely, errors in the model normalization, unexpected luminosity evolution (at low and high redshifts), errors in the photometry, incompleteness and large-scale structure. In order to address the issue of the model normalization, we examine the number counts determined for the new faint photometry presented in this work and also for faint data ($H \lesssim 20$) covering 0.39 deg$^2$ from the Las Campanas Infrared Survey (LCIRS). In each case a zero-point is chosen to match that of the 2MASS photometry at bright magnitudes using several hundred matched point sources in each case. We find a large offset between 2MASS and the LCIRS data of 0.28 $\pm$ 0.01 mag. Applying a consistent zero-point, the faint data, covering a combined solid angle of 0.69 deg$^2$, is in good agreement with the homogeneous prediction used previously, with a best-fitting normalization a factor of $1.095^{+0.035}_{-0.034}$ higher. Addressing the contribution from large-scale structure, we estimate the cosmic variance in the bright counts over the APM survey area and for $|b| > 20^\circ$ expected in a Lambda cold dark matter ($\Lambda$CDM) cosmology using 27 mock 2MASS catalogues constructed from the $\Lambda$CDM Hubble Volume simulation. The APM survey area bright counts are in line with a rare fluctuation in the local galaxy distribution of $\approx 2–3\sigma$. The $|b| > 20^\circ$ counts represent a 2.5–4$\sigma$ fluctuation and would imply a local hole which extends over the entire local galaxy distribution, which may start to be at odds with $\Lambda$CDM. The increase in faint near-infrared data from the UK Infrared Deep Sky Survey should help to resolve this issue.

Key words: galaxies: photometry – cosmology: observations – large-scale structure of Universe – infrared: galaxies.

1 INTRODUCTION

A recurring problem arising from the study of bright galaxy number counts has been the measured deficiency of galaxies around the southern Galactic pole. This was first examined in detail by Shanks (1990) and subsequently by the APM galaxy survey (Maddox et al. 1990a), which observed a large deficit in the number counts ($\approx 50$ per cent at $B = 16$, $\approx 30$ per cent at $B = 17$) over a $\approx 4000$-deg$^2$ solid angle. If this anomaly was due solely to features in the galaxy distribution, this would be at odds with recent measurements of the variance of local galaxy density fluctuations (e.g. Hawkins et al. 2003; Cole et al. 2005; Frith, Outram & Shanks 2005b) or the expected linear growth of density inhomogeneities at large scales.

Maddox et al. (1990b) examined possible causes of this deficiency. From redshift survey results over the APM survey area (Loveday et al. 1992), it was argued that a weak local underdensity contributed to the observed deficiency at the $\lesssim 10$ per cent level at $B \approx 17$. Instead, Maddox et al. (1990b) suggested that strong low-redshift galaxy evolution was the dominant contribution. This phenomenon has also been suggested as a possible explanation for...
large deficiencies in the Sloan Digital Sky Survey (SDSS; Loveday 2004), although models without such strong low-redshift evolution provide predictions consistent with observed number–redshift distributions (e.g. Broadhurst, Ellis & Shanks 1988; Colless et al. 1990; Hawkins et al. 2003). In contrast, Shanks (1990) argued that evolution could not account for the observed slope and that large-scale structure was the principal cause of the deficiency in the counts.

However, another possible contribution to the low counts might be errors in the APM photometry. Comparing the photographic APM photometry with $B$-band CCD data, Metcalfe, Fong & Shanks (1995) detected a small residual scale error in the APM survey zero-points for $B > 17$. Correcting for this offset, the counts were now in good agreement with homogeneous predictions at faint magnitudes ($B > 17.5$); however, the problematic deficiency at brighter magnitudes remained. More recently, Busswell et al. (2004) used $B$-band CCD data over $\approx 337$ deg$^2$ within the APM survey area to provide the most accurate comparison to date with a sample of the APM survey photometry. The photometric zero-point of this CCD data was in excellent agreement with the Millennium Galaxy Catalogue (Driver 2003) and the Sloan Digital Sky Survey Early Data Release (Yasuda et al. 2001). However, a comparison with the APM photometry suggested a large offset of 0.31 mag for $B < 17.35$. Applying this to the APM survey counts, a deficiency of $\approx 25$ per cent remained at $B = 16$; Busswell et al. (2004) determined that such a deficiency in the local galaxy distribution would still be at odds with a Lambda cold dark matter ($\Lambda$CDM) form to the galaxy correlation function and power spectrum at large scales.

In order to examine this issue independently, bright number counts have also been examined in the near-infrared (Frith et al. 2003; Frith, Outram & Shanks 2004; Frith, Shanks & Outram 2005a). These wavelengths are particularly useful for such analysis as the number count predictions are fairly insensitive to the evolutionary model at bright magnitudes (see Fig. 1); current observations are in remarkable agreement with predictions in the $K$ band to $K \approx 23$ (e.g. McCracken et al. 2000). In particular, Frith et al. (2005a) examined $K$-band number counts selected from the two-Micron All-Sky Survey (2MASS; Jarrett 2004). First, the counts over the APM survey area were determined; a similar deficiency was observed to the APM survey counts [with the zero-point offset determined by Busswell et al. (2004) applied], with a $\approx 25$ per cent deficit at $K_s = 12$ compared to the no evolution model of Metcalfe et al. (2001). Using a $\Lambda$CDM form for the angular correlation function at large scales and assuming the observed counts were solely due to features in the local galaxy distribution, the observed counts represented a 5$\sigma$ fluctuation. However, this result was complicated by the fact that the 2MASS $K_s$-band number counts for almost the entire survey ($|b| > 20^\circ$, covering $\approx 27000$ deg$^2$) were also low, with a constant deficiency of $\approx 20$ per cent between $K_s = 10$ and $K_s = 13.5$.

Did this surprising result perhaps indicate that the $K_s$-band Metcalfe et al. (2001) model normalization was too high? Or, as suggested previously, could low-redshift luminosity evolution significantly affect the bright counts? These issues were also addressed by Frith et al. (2005a), First, the Metcalfe et al. (2001) model was compared with faint $K$-band data collated from the literature. Fitting in the magnitude range $14 < K < 18$ it was found that the best-fitting model normalization was slightly too high, although not significantly (this magnitude range was used so as to avoid fluctuations in the counts arising from large-scale structure at bright magnitudes and significant effects from galaxy evolution at the faint end). Accounting for the normalization uncertainty (of $\pm 6$ per cent) the observed deficiency in the $K_s$-band counts over the APM survey area still represented a $\approx 3\sigma$ fluctuation. Secondly, the issue of low-redshift luminosity evolution was also addressed: 2MASS galaxies below $K_s = 13.5$ were matched with the northern and southern areas of the 2dF Galaxy Redshift Survey (2dFGRS; Colless et al. 2003). The resulting $n(z)$, covering $> 1000$ deg$^2$ in total, was consistent with the no evolution model of Metcalfe et al. (2001). In addition, these $K_s$-band redshift distributions were used to form predictions for the number counts over the northern and southern 2dFGRS areas, respectively. This was done by multiplying the luminosity function parameter $\phi^*$ (which governs the model normalization) used in the Metcalfe et al. (2001) model by the relative density observed in the $K_s$-band $n(z)$ as a function of redshift. These ‘variable $\phi^*$ models’ were then compared with 2MASS counts extracted for the 2dFGRS areas in order to determine whether the observed counts were consistent with being due solely to features in the local galaxy distribution; the variable $\phi^*$ models were in good agreement with the number counts, lessening any need for strong, low redshift, luminosity evolution to be invoked to explain the observed deficiency in the counts.

In this paper we aim to address the issue of low, bright number counts in the near-infrared $H$-band. In particular we wish to address a drawback to the $K_s$-band analysis of Frith et al. (2005a) – the issue of the number count model normalization; while the $K_s$-band model used was compared with faint data and was found to be in good agreement, the level to which systematic effects, arising perhaps via zero-point offsets between the bright and faint data or cosmic variance in the faint data, might affect the conclusions were uncertain. We address this issue in the $H$ band using new faint data covering 0.3 deg$^2$ to $H = 18$, calibrated to match the 2MASS zero-point. In Section 2, we first verify that the $H$-band counts provide number counts over the APM survey area which are consistent with the previous results in the $B$ and $K_s$ bands (Busswell et al. 2004; Frith et al. 2005a), and that the form of the counts is not significantly affected by low-redshift luminosity evolution through comparisons with the variable $\phi^*$ models described above. In Section 3, we provide details of the data reduction of the new faint $H$-band photometry. The associated counts are presented in

Figure 1. $H$-band galaxy number counts collated from the literature. The dashed and solid lines indicate the no evolution and pure luminosity evolution predictions, respectively, described in Section 2. We also show bright $H$-band counts extracted from the 2MASS extended source catalogue for $|b| > 20^\circ$. For each data set, we indicate the associated observed solid angle in square brackets.
In Section 4, in Section 5, we discuss possible systematics affecting the bright number counts including the model normalization and incompleteness. The conclusions follow in Section 6.

2 BRIGHT H-BAND COUNTS FROM 2MASS

We wish to examine the form of bright number counts in the H band in order to verify that the counts over the APM survey area (≈4000 deg$^2$ around the southern Galactic pole) are comparable to those measured previously in the optical $B$ band and near-infrared $K_s$ band (Busswell et al. 2004; Frith et al. 2005a). The near-infrared has the advantage of being sensitive to the underlying stellar mass and is much less affected by recent star formation history than optical wavelengths. For this reason, number count predictions in the near-infrared are insensitive to even passive luminosity evolution models at bright magnitudes. In Fig. 1 we show faint H-band data collated from the literature along with bright counts extracted from 2MASS over ≈27 000 deg$^2$. The 2MASS magnitudes are determined via the 2MASS $H$-band extrapolated magnitude; this form of magnitude estimator has previously been shown to be an excellent estimate of the total flux in the $K_s$ band (Frith, Outram & Shanks 2005b,c) through comparison with the total magnitude estimates of Jones et al. (2004) and the $K$-band photometry of Loveday (2000). Throughout this paper we use 2MASS $H$-band counts determined via this magnitude estimator. We also show two models in Fig. 1 corresponding to homogeneous predictions assuming no evolution and pure luminosity evolution models. These are constructed from the $H$-band luminosity function parameters listed in Metcalfe et al. (2006) and the $(K + E)$-corrections of Bruzual & Charlot (1993). At bright magnitudes the two are indistinguishable; only at $H > 18$ do the model predictions begin to separate. The faint data are in good agreement with both the no-evolution and pure luminosity evolution predictions to $H \approx 26$.

Before examining the $H$-band counts over the APM survey area, we first verify that the bright counts are consistent with relatively insignificant levels of low-redshift luminosity evolution in the manner carried out by Frith et al. (2005a) for the $K_s$-band counts. In the upper panels of Fig. 2 we show $H$-band $n(z)$ to the 2MASS limiting magnitude of $H = 14$, determined through matched 2MASS and 2dFGRS galaxies over the 2dFGRS northern (left-hand panel) and southern (right-hand panels) declination strips [see Frith et al. (2005a) for further details of the matching technique]. The solid lines indicate the expected homogeneous distribution constructed from the pure luminosity evolution predictions of Metcalfe et al. (2006) (there is no discernible difference between this and the no-evolution prediction). In the lower panels we divide through by this prediction; these panels show the relative density as a function of redshift. The observed $n(z)$ are consistent with the expected trends, with relatively homogeneous distributions beyond $z = 0.1$ (1 and 8 per cent overdense in the north and south, respectively, for $0.1 \leq z \leq 0.2$). For this reason, Fig. 2 suggests that the level of luminosity evolution is relatively insignificant at low redshifts in the $H$ band; strong luminosity evolution produces an extended tail in the predicted $n(z)$ which is not observed in the data.

As a further check against strong low-redshift luminosity evolution, we can use the observed $n(z)$ to predict the expected $H$-band number counts over the 2dFGRS declination strips. This technique is described in detail in Frith et al. (2003, 2005a). To recap, we use the observed density (Fig. 2, lower panels), to vary the luminosity function normalization ($\phi_0$) used in the Metcalfe et al. (2006) model as a function of redshift (for $z \leq 0.2$). We show these ‘variable $\phi_0$’ models along with the 2MASS $H$-band counts extracted for the 2dFGRS strips in Fig. 3. In each case, the upper panels indicate the number count on a logarithmic scale; in the lower panels we divide through by the homogeneous prediction. In both the northern and southern 2dFGRS areas, the counts are in good agreement with the expected trend, defined by the corresponding variable $\phi_0$ model. This is at least consistent with the idea that real features in the local galaxy distribution, rather than luminosity evolution, are the dominant factor in explaining the form of the observed $H$-band number counts.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Number–redshift histograms for 11 501 and 13 687 $H<14$ 2MASS galaxies matched with the 446-deg$^2$ northern (left-hand panel) and 647-deg$^2$ southern (right-hand panel) 2dFGRS declination strips, respectively. In each case the solid lines indicate the pure luminosity evolution prediction for a homogeneous distribution described in Section 2 normalized by the respective solid angles. We also indicate the relative density in the lower panels, dividing the observed $n(z)$ by the homogeneous prediction.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** $H$-band 2MASS galaxy number counts extracted from the northern (left-hand panel) and southern (right-hand panel) 2dFGRS declination strips. The solid line indicates the homogeneous pure luminosity evolution prediction described in Section 2 (this and the no-evolution prediction are indistinguishable at these magnitudes). The dashed and dot–dashed lines indicate the variable $\phi_0$ models for the northern and southern 2dFGRS strips, respectively; these indicate the expected number counts given the observed $n(z)$ (Fig. 2). In the lower panels we divide through by the homogeneous prediction. In each case the error bars indicate the Poisson uncertainty in each bin.
3 NEW FAINT $H$-BAND DATA

3.1 Observations and data reduction

Our data were taken during a three-night observing run in 2004 September at the f/3.5 prime focus of the Calar Alto 3.5-m telescope in the Sierra de Los Filabres in Andalucia, southern Spain. The Ω-2000 infrared camera contains a 2048 × 2048 pixel HAWII-2 Rockwell detector array, with 18.5-μm pixels, giving a scale of 0.45 arcsec pixel$^{-1}$ at the prime focus. All observations were taken with the $H$-band filter. Poor weather meant that only just over one night’s worth of data were usable, and even then conditions were not photometric.

Our primary objective was to image the William Herschel Deep Field as deeply as possible (the results of which are presented in a forthcoming paper), but time was available at the start of each night to image several ‘random’ fields for 15 min each. These were composed of individual 3-s exposures, stacked in batches of 10 before readout. A dithering pattern on the sky with a shift up to ±25 arcsec around the nominal centre was adopted.

Data reduction was complicated by the fact that both the dome and twilight sky flat-fields appeared to have a complicated out-of-focus pattern of the optical train imprinted upon them (probably an image of the top end of the telescope). This appeared (in reverse) in the science data if these frames were used for flat-fielding. We therefore constructed a master flat-field by mediating together all the science frames from a particular night. This was then used to flat-field all the data. Then, individual running medians were constructed from batches of 10 or so temporally adjacent frames, and these were subtracted from each frame to produce a flat, background subtracted image. These were then aligned and stacked together (with sigma clipping to remove hot pixels). Image detection and analysis is done using the SExtractor software package v2.3.2 (Bertin & Arnouts 1996), run via the Starlink GAIA interface. The adopted magnitudes are SExtractor ‘auto’ magnitudes.

3.2 Calibration

Photometric calibration of the $H$-band images is obtained through comparison with the 2MASS point source catalogue. Fig. 5 shows the 2MASS ‘default’ point source magnitudes compared with our data for 393 matched point sources over the Calar Alto field and the William Herschel Deep Field. The zero-point of our data is chosen

![Figure 4.](https://example.com/figure4.png) **Figure 4.** $H$-band 2MASS galaxy number counts extracted for the APM survey area ($\approx$4000 deg$^2$) and for $|b| > 20^\circ$ ($\approx$27 000 deg$^2$), shown in the left- and right-hand panels, respectively. As in Fig. 2, we show the homogeneous pure luminosity prediction (solid line), and the northern (dashed line) and southern (dot-dashed line) variable $\phi^*$ models, indicating the expected number counts for the redshift distributions shown in Fig. 2. As before, in the lower panels we divide through by the homogeneous prediction. In each case the error bars indicate the Poisson uncertainty in each bin.

![Figure 5.](https://example.com/figure5.png) **Figure 5.** The uncertainty in the photometric calibration with 2MASS. The $H$-band magnitudes determined by 2MASS and the residual with our photometry are indicated for 393 point sources below $H = 15.1$. The large data points indicate the mean offset and rms dispersion as a function of magnitude. The zero-point used is indicated by the solid line and is accurate to ±0.01 mag at 1σ confidence.
to match that of the 2MASS objects and is accurate to ±0.01 mag. The large data points and error bars indicate the mean offset and rms dispersion as a function of magnitude. When comparing these data to the 2MASS number counts at bright magnitudes it is important to note that the 2MASS point source catalogue includes a maximum bias in the photometric zero-point of <2 per cent around the sky (see the 2MASS website).

3.3 Star/galaxy separation
We use the SExtractor software to separate objects brighter than \( H = 18 \); for this magnitude limit, the associated STAR_CLASS parameter provides a reliable indicator of stars and galaxies. We identify 30.0 per cent as galaxies (CLASS_STAR < 0.1), 58.9 per cent as stars (CLASS_STAR > 0.9), leaving 11.1 per cent as unclassified.

4 FAINT \( H \)-BAND COUNTS

4.1 Comparison with the LCIRS
Before determining number counts for the new \( H \)-band data described in Section 3, we first examine the photometry of the Las Campanas Infrared Survey (LCIRS; Chen et al. 2002). The published data cover 847 arcmin\(^2\) in the Hubble Deep Field-South (HDF-S) and 561 arcmin\(^2\) in the Chandra Deep Field-South (CDF-S); the combined solid angle (0.39 deg\(^2\)) represents the largest \( H \)-band photometry for \( 14 \leq H \leq 20 \). The associated number counts are \( \approx 15 \) per cent below the homogeneous Metcalfe et al. (2006) predictions at \( H = 18 \) (see Fig. 1). This is significant, as if the model normalization was altered to fit, the deficiency in the 2MASS counts at bright magnitudes (Fig. 3) would become much less severe. However, various other surveys show higher counts, although over much smaller solid angles. With the LCIRS data in particular therefore, it is vital to ensure that the photometric zero-point is consistent with the 2MASS data at bright magnitudes.

In Fig. 6 we compare the LCIRS and 2MASS \( H \)-band photometry for 438 points sources matched over the HDF-S and CDF-S fields (as in Fig. 5 we use the 2MASS ‘default’ point source catalogue magnitudes, here compared with the LCIRS ‘best’ magnitudes). There appears to be a large offset which is approximately constant for \( H > 12 \). Using point sources matched at all magnitudes, we determine a mean offset of \(-0.28 \pm 0.01\) mag; this is robust to changes in the magnitude range and is consistent over both the HDF-S and CDF-S fields.

4.2 New \( H \)-band counts

In Fig. 7, we show counts determined for the new \( H \)-band data described in Section 3, the 0.27-deg\(^2\) CA field and the 0.06-deg\(^2\) WHDF (see also Table 1). Both sets of counts are in excellent agreement with the pure luminosity evolution and no evolution homogeneous predictions of Metcalfe et al. (2006). In addition, we show LCIRS counts determined in the 0.24-deg\(^2\) HDF-S and 0.16-deg\(^2\) CDF-S, applying the 0.28-mag zero-point offset determined with respect to 2MASS in Section 4.1. The associated counts are also in excellent agreement with the Metcalfe et al. (2006) models at all magnitudes.

In Fig. 8, we show counts determined from our data and the LCIRS combined, with a consistent zero-point applied as in Fig. 7. We estimate the uncertainty arising from cosmic variance using field-to-field errors, weighted by the solid angle of each field. These combined counts are in good agreement with the Metcalfe et al. (2006) models, particularly at fainter magnitudes where the dispersion in the counts arising from cosmic variance appears to be small. We perform least squares fits between these counts and the pure luminosity evolution model; in the magnitude range \( 14 < H < 18 \)

![Figure 6. The \( H \)-band photometry of the LCIRS (Chen et al. 2002) with 2MASS using 438 point sources. As in Fig. 5, the large data points indicate the mean offset and rms dispersion as a function of magnitude. The mean offset is \(-0.28 \pm 0.01\) mag at 1σ confidence. The zero-point used in the new data presented in this work is indicated by the solid line.](https://academic.oup.com/mnras/article-abstract/371/4/1601/1056265)

![Figure 7. \( H \)-band galaxy number counts for the two separate fields observed in this work, the Calar Alto field (CA field; 0.27 deg\(^2\)) and the William Herschel Deep field (WHDF; 0.06 deg\(^2\)). We also show number counts determined for the two separate fields of the LCIRS (Chen et al. 2002) situated in the HDF-S (0.24 deg\(^2\)) and CDF-S (0.16 deg\(^2\)), subtracting 0.28 mag in each case in order to bring the LCIRS and 2MASS zero-points (and hence also the CA field and WHDF zero-points) into agreement. We also show bright number counts extracted from 2MASS for the APM survey area and for \( |b| > 20\degree \) as shown in Fig. 3. The models are indicated as in Fig. 1. In the lower panel, we divide through by the pure luminosity evolution homogeneous prediction as in Figs 3 and 4. At faint magnitudes, we indicate the Poisson uncertainty in each bin. We omit Poisson errors on the bright counts for clarity (see Fig. 4 for these). We discuss the uncertainty in the counts arising from cosmic variance in Section 5.](https://academic.oup.com/mnras/article-abstract/371/4/1601/1056265)
Table 1. The raw number counts per half magnitude are shown for the new H-band data described in Section 3—the CA field (0.27 deg$^2$) and WHDF (0.06 deg$^2$) in columns 2 and 3. In addition, we show the counts for the LCIRS fields, the HDFS (0.24 deg$^2$) and CDF-S (0.16 deg$^2$) in columns 4 and 5, applying the zero-point offset determined with respect to 2MASS in Section 4.1. The total number count per deg$^2$ for all fields combined (0.69 deg$^2$) is shown in column 6 along with the homogeneous pure luminosity evolution prediction of Metcalfe et al. (2006) in column 7. The faintest magnitude bin for the CA field is slightly smaller (0.21 deg$^2$) than at brighter magnitudes; the combined solid angle for the faintest bin in column 6 is therefore 0.66 deg$^2$.

| H   | $N_{\text{CA field}}$ | $N_{\text{WHDF}}$ | $N_{\text{HDFS}}$ | $N_{\text{CDF-S}}$ | $N_{\text{tot}}$ [deg$^{-2}$ (0.5 mag)$^{-1}$] | $N_{\text{mod}}$ [deg$^{-2}$ (0.5 mag)$^{-1}$] |
|-----|------------------------|---------------------|-------------------|-------------------|-----------------------------------------------|-----------------------------------------------|
| 14.25 | 10                     | 4                   | 6                 | 8                 | 40.8                                          | 23.0                                          |
| 14.75 | 17                     | 5                   | 12                | 8                 | 61.1                                          | 43.5                                          |
| 15.25 | 21                     | 9                   | 23                | 23                | 110                                           | 81.9                                          |
| 15.75 | 41                     | 14                  | 31                | 43                | 188                                           | 153                                          |
| 16.25 | 55                     | 15                  | 77                | 51                | 288                                           | 280                                          |
| 16.75 | 133                    | 39                  | 163               | 73                | 594                                           | 500                                          |
| 17.25 | 217                    | 58                  | 238               | 135               | 943                                           | 861                                          |
| 17.75 | 283                    | 77                  | 337               | 256               | $1.44 \times 10^3$                           | $1.43 \times 10^3$                            |

Figure 8. The faint H-band data from the two fields presented in this work (CA field and WHDF) and the two fields published by the LCIRS (HDF-S and CDF-S; Chen et al. 2002), applying a zero-point to the LCIRS data consistent with the bright H-band 2MASS data (and hence the CA field and WHDF also), as shown in Fig. 7. The error bars at faint magnitudes indicate the field-to-field error, weighted in order to account for the different solid angles of each field. Bright H-band counts extracted from 2MASS for the APM survey area and for $|b| > 20^\circ$ are shown as previously. In the lower panel, the counts are divided through by the pure luminosity evolution homogeneous prediction as before.

we find a best-fitting normalization of $1.095^{+0.035}_{-0.034}$, where 1.0 corresponds to the Metcalfe et al. (2006) normalization shown in Fig. 8. Varying the fitting range does slightly alter the result; in the range $16 < H < 18$ we find a best-fitting normalization of $1.061^{+0.048}_{-0.033}$ for example.

5 DISCUSSION

In the previous sections, bright H-band number counts from 2MASS were determined over the APM survey area ($\approx$4000 deg$^2$) and almost the entire 66 per cent of the sky ($|b| > 20^\circ$, $\approx$27 000 deg$^2$), along with faint counts to $H = 18$ over a combined solid angle of 0.69 deg$^2$ applying a zero-point consistent with 2MASS. The bright H-band number counts over the APM survey area are extremely low ($\approx$25 per cent at $H = 13$) with respect to homogeneous predictions, and reproduce the form of the bright counts observed in the optical $B$ band (Busswell et al. 2004) and the near-infrared $K_s$ band (Frith et al. 2005a). Previous work has suggested that, if due solely to local large-scale structure, these low counts would be at odds with the form of clustering expected in a $\Lambda$CDM cosmology. In addition, the bright H-band $|b| > 20^\circ$ counts were also found to be low. In the following section, various possible causes for these low counts are examined.

5.1 Model normalization

The normalization of number count models may be determined by fixing the predicted to the observed number of galaxies at faint magnitudes. The magnitude range at which this is done should be bright enough to avoid large uncertainties in the evolutionary model while faint enough such that large fluctuations in the counts arising from cosmic variance are expected to be small. Near infrared wavelengths are expected to be insensitive to luminosity evolution at bright magnitudes, making the $H$ band particularly useful for such analysis. Of vital importance when determining the model normalization is that when making comparisons between faint and bright counts, the zero-points are consistent; an offset of a few tenths of a magnitude between the two, for example, would be enough to remove the observed anomaly in the bright counts over the APM survey area.

Applying the 2MASS zero-point to the faint H-band data presented in this work and the LCIRS data (Chen et al. 2002), covering a combined solid angle of 0.69 deg$^2$, it is clear that a discrepancy between the bright and faint counts exists; the model normalization used previously, which indicates low counts for $H < 14$ over the APM survey area (and for $|b| > 20^\circ$), provides good agreement with the faint data. In fact, fixing the model to the faint counts implies a slightly higher normalization of $1.095^{+0.035}_{-0.034}$ (determined for $14 < H < 18$ using field-to-field errors).

In addition, the model normalization may also be scrutinized through comparison with redshift distributions. Fig. 2 shows the Metcalfe et al. (2006) pure luminosity evolution model compared with H-band $n(z)$ determined through a match between 2MASS and the 2dFGRS northern and southern declination strips. The
model predictions appear to be consistent with the observations, with relatively homogeneous distributions beyond $z = 0.1$ (1 and 8 per cent overdense in the north and south, respectively). Lowering the model normalization to fit the bright 2MASS number counts would compromise this agreement and imply large overdensities beyond $z = 0.1$ (19 and 27 per cent in the north and south, respectively).

5.2 Galaxy evolution

A change in normalization therefore, cannot easily account for the discrepancy in the number counts at bright magnitudes. However, could an unexpected change in the slope of the number count model contribute? In Section 2, we examined the consistency of the number counts at bright magnitudes with the underlying redshift distribution, assuming a model with insignificant levels of luminosity evolution at low redshift. The predictions derived from the observed $n(z)$ were in good agreement with the observed number counts indicating that luminosity evolution at low redshift is unlikely to have a significant impact on the form of the counts at bright magnitudes. This is supported by the consistency of the pure luminosity evolution model with the observed redshift distributions (Fig. 2); strong low-redshift luminosity evolution produces a tail in the $n(z)$ which would imply large deficiencies at high redshift.

Could unexpectedly high levels of luminosity evolution at higher redshifts affect our interpretation of the bright counts? If the slope of the homogeneous prediction were to increase significantly above $H \approx 14$ from the evolutionary models considered in this paper, then the model normalization could effectively be lowered into agreement with the bright counts. The problem with this is that the number counts beyond $H \approx 14$ are consistent with low levels of luminosity evolution to extremely faint magnitudes ($H \approx 26$). Models with significantly higher levels of luminosity evolution above $H \approx 14$ would therefore compromise this agreement.

Therefore, it appears that relatively low levels of luminosity evolution are consistent with number count observations to high redshifts. Also, recent evidence from the COMBO-17 survey, examining the evolution of early-type galaxies using nearly 5000 objects to $z \approx 1$ (Bell et al. 2004), suggests that density evolution will also not contribute; $\Phi^{*}$ appears to decrease with redshift indicating that the number of objects on the red sequence increases with time, and so acts contrary to the low counts observed at bright magnitudes. This picture is supported by the K20 survey (Cimatti et al. 2002), which includes redshifts for 480 galaxies to a mean depth of $z \approx 0.7$ and a magnitude limit of $K_*= 20$ with high completeness. The resulting redshift distribution is consistent with low levels of luminosity and density evolution (Metcalfe et al. 2006).

In summary, significant levels of evolution are not expected in passive or star-forming pure luminosity evolution models, although could occur through dynamical evolution. However, the pure luminosity evolution models of Metcalfe et al. (2006) fit the observed $H < 14$ n(z) at $z > 0.1$; it is at lower redshifts that there are fluctuations. In addition, these models continue to fit the observed n(z) at very high redshift and the number counts to extremely faint magnitudes ($K \approx 23$), suggesting that there is little need for evolution at $z \approx 1$, far less $z \lesssim 0.1$. Some combination of dynamical and luminosity evolution might be able to account for these observations; however it would require fine-tuning in order to fit both the steep counts at bright magnitudes and the unevolved $n(z)$ at low and high redshifts.

5.3 Photometry issues and completeness

The number counts shown in Figs 7 and 8 show bright and faint counts with a consistent zero-point applied. Photometry comparisons have been made using several hundred point sources matched at bright magnitudes. In order to check that the applied zero-points are consistent with the galaxy samples, we also compare the 2MASS photometry with 24 matched galaxies in the CA field and WHDF and 16 in the LCIRS samples; we find that the mean offsets are $-0.01 \pm 0.04$ and $-0.32 \pm 0.06$, consistent with the zero-points determined via the 2MASS point sources. The comparisons with the 2MASS point source catalogue (Figs 5 and 6) also indicate that there is no evidence of scale error in either of the faint samples to $H \approx 16$.

Could the discrepancy between the bright and faint counts arise from an underestimation of the total flux of the galaxies? Recall that we make no correction to total magnitude for the faint data presented in this work; however, underestimating the total flux in the faint data would only increase the observed deficit in the counts at bright magnitudes, if the model normalization is adjusted to fit the faint counts. The good agreement between the point source and galaxy zero-points suggests that the estimate for the total galaxy flux is comparable in the bright and faint data. At bright magnitudes, the 2MASS extrapolated $H$-band magnitudes are used. In the $K_*$ band, this magnitude estimator has been shown to be an excellent estimate of the total flux, through comparisons with the total $K_*$-band magnitude estimator of Jones et al. (2004) and the K-band photometry of Loveday (2000).

Another possible contribution to the low counts could be high levels of incompleteness in the 2MASS survey. As with the possible systematic effects described previously, it is differing levels of completeness in the faint and bright data which would be important. The 2MASS literature quotes the extended source catalogue completeness as $>90$ per cent (see the 2MASS website for example). Independently, Bell et al. (2003) suggest that the level of completeness is high ($\approx 99$ per cent), determined via comparisons with the SDSS Early Data Release spectroscopic data and the 2dFGRS. The faint data presented in this work and the LCIRS data are likely to suffer less from incompleteness, as we cut well below the magnitude limit, are subject to lower levels of stellar confusion and suffer less from low-resolution effects. Incompleteness in 2MASS will therefore affect the observed deficit in the bright counts at the $<10$ per cent level, although the effect is likely to be at the low end of this constraint due to incompleteness in the faint catalogues and suggestions that the 2MASS extended source catalogue is fairly complete.

5.4 Large-scale structure

It appears therefore, that the observed deficiency in the bright counts might be significantly affected by incompleteness in the 2MASS extended source catalogue. However, the level to which other systematic effects such as the model normalization, luminosity evolution and photometry issues appears to be small. The question then is—accounting for these various sources of error or uncertainty, are the deficiencies in the bright $H$-band counts over the APM survey area for $|b| > 20^\circ$ still at odds with the expected fluctuations in the counts arising from local large-scale structure in a $\Lambda$CDM cosmology, as suggested in previous work (Busswell et al. 2004; Frith et al. 2005a)? We determine the expected fluctuations in the bright number counts due to cosmic variance via $\Lambda$CDM mock 2MASS catalogues; these are described in detail in Frith et al. (2005a). To recap, we apply the 2MASS selection function to 27 virtually independent
volumes of $r = 500 \, h^{-1} \, \text{Mpc}$ formed from the $3000^3 \, h^{-3} \, \text{Mpc}^3$ ΛCDM Hubble Volume simulation. This simulation has input parameters of $\Omega_m = 0.3$, $\Omega_b = 0.04$, $h = 0.7$ and $\sigma_8 = 0.9$ (Jenkins et al. 1998). The mean number density of the counts at the magnitude limit is set to that of the observed 2MASS density.

We are now in a position to estimate the significance of the observed bright $H$-band counts. We use the $1\sigma$ fluctuation in the counts expected in a ΛCDM cosmology (determined using the 2MASS mocks described above), which for the APM survey area is $7.63$ per cent (for $H < 13$) and $4.79$ per cent (for $H < 14$), and for $|b| > 20^\circ$ is $3.25$ per cent (for $H < 13$) and $1.90$ per cent (for $H < 14$). In addition we also take into account the uncertainty in the model normalization; we use the best-fitting normalization of the Metcalfe et al. (2006) pure luminosity evolution model [a factor of $1.095$ above the Metcalfe et al. (2006) model] and add the uncertainty of $\pm 6.0$ per cent appropriate for the faint $H$-band counts in quadrature. This latter normalization uncertainty is obtained from equation (36.6) of Peebles (1980), assuming a $-0.8$ power law and amplitude $B = 0.0025 \, h^{-0.8}$ for the 2D correlation function, and based on the observed $0.69$-deg$^2$ area of sky, assumed to be subdivided into four equal, square areas. This error is $\approx 2$ times bigger than the field–field error of $\pm 3.1$ per cent from the faint $H$ counts themselves, presented in Fig. 8, and as used in Section 5.1.

Regarding the possible effect arising from survey incompleteness, we first assume that the level of incompleteness is comparable in the faint and bright data; the resulting significance for the APM survey area and $|b| > 20^\circ$ bright counts are shown in column 3 of Table 2. This represents an upper limit on the significance since we have effectively assumed that there is no difference in the incompleteness between the bright and faint data sets. In column 4 of Table 2, we assume that there is a difference in the completeness levels in the faint and bright data of 10 per cent. This represents a lower limit on the significance (assuming that there are no further significant systematic effects), since we assume that the completeness of the 2MASS extended source catalogue is 90 per cent (the lower limit) and that there is no incompleteness in the faint data.

Therefore, assuming a ΛCDM cosmology, it appears that the observed counts over the APM survey area might be in line with a rare fluctuation in the local galaxy distribution. However, the counts over 66 per cent of the sky ($|b| > 20^\circ$) suggest a deficiency in the counts that may be at odds with ΛCDM, even accounting for a 10 per cent incompleteness effect and the measured uncertainty in the best-fitting model normalization.

### Table 2. The significance of the $H$-band 2MASS counts extracted for the $\approx 4000$-deg$^2$ APM survey area and for $|b| > 20^\circ$, for $H < 13$ and $H < 14$.

| Field | $H_{\text{lim}}$ | Significance (no incompleteness correction) | Significance (assuming 10 per cent incompleteness) |
|-------|-----------------|---------------------------------------------|-----------------------------------------------|
| APM   | 13.0            | $3.2\sigma$                                 | $2.1\sigma$                                   |
| APM   | 14.0            | $3.1\sigma$                                 | $1.8\sigma$                                   |
| $|b| > 20^\circ$ | 13.0 | $4.0\sigma$ | $2.6\sigma$ |
| $|b| > 20^\circ$ | 14.0 | $4.0\sigma$ | $2.4\sigma$ |

In contrast, the bright $H$-band counts extracted from 2MASS over the $\approx 4000$-deg$^2$ APM survey area around the southern Galactic pole are low with respect to this model, corroborating previous results over this area in the optical $B$ band and near-infrared $K_s$ band (Busswell et al. 2004; Frith et al. 2005a). In addition, the counts extracted for almost the entire survey, covering 66 per cent of the sky, are also low with a deficit of $15–20$ per cent at $H = 14$. Importantly, this discrepancy does not appear to be due to zero-point differences between the faint and bright data or uncertainty in the model normalization set by the faint counts.

We have investigated various possible sources of systematic error which might affect this result. The counts are consistent with low levels of luminosity and density evolution, as predicted by the pure luminosity evolution model of Metcalfe et al. (2006), to extremely faint magnitudes (see Fig. 1). Also, the photometry appears to be consistent between the faint and bright galaxy data using a zero-point applied via comparisons between point sources. However, differing incompleteness in the bright and faint galaxy samples might have a significant impact; completeness in the 2MASS extended source catalogue is $\approx 90$ per cent.

Finally, we determined the expected cosmic variance in the bright number counts from ΛCDM mock 2MASS catalogues. Allowing for uncertainty in the model normalization derived from the faint counts, the deficiency in the counts over the APM survey area represents an $\approx 2$–$3\sigma$ fluctuation in a ΛCDM cosmology, depending on whether allowance is made for 2MASS incompleteness. Moreover, the low $H$-band counts for $|b| > 20^\circ$ suggest that this deficiency might extend over the entire local galaxy distribution; allowing for the model normalization uncertainty as before, this would represent an $\approx 2.5$–$4\sigma$ fluctuation in the local galaxy distribution and start to be at odds with the expected form of clustering expected in a ΛCDM cosmology on large scales. The increase in faint near-infrared data from the UK Infrared Deep Sky Survey should help to resolve this issue.

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