NEAR-INFRARED GALAXY COUNTS AND EVOLUTION FROM THE WIDE-FIELD ALHAMBRA SURVEY*

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ABSTRACT

The ALHAMBRA survey aims to cover 4 deg^2 using a system of 20 contiguous, equal width, medium-band filters spanning the range 3500 Å–9700 Å plus the standard JHKs filters. Here we analyze deep near-IR number counts of one of our fields (ALH08) for which we have a relatively large area (0.5 deg^2) and faint photometry (\(J = 22.4\), \(H = 21.3\), and \(K = 20.0\) at the 50\% of recovery efficiency for point-like sources). We find that the logarithmic gradient of the galaxy counts undergoes a distinct change to a flatter slope in each band: from 0.44 at [17.0, 18.5] to 0.34 at [19.5, 22.0] for the \(J\) band; for the \(H\) band 0.46 at [15.5, 18.0] to 0.36 at [19.0, 21.0], and in \(K\) the change is from 0.53 in the range [15.0, 17.0] to 0.33 in the interval [18.0, 20.0]. These observations together with faint optical counts are used to constrain models that include density and luminosity evolution of the local type-dependent luminosity functions. Our models imply a decline in the space density of evolved early-type galaxies with increasing redshift, such that only 30\%–50\% of the bulk of the present day red ellipticals was already in place at \(z \sim 1\). Keywords: cosmology: observations – galaxies: evolution – galaxies: high-redshift – galaxies: photometry – infrared: galaxies – surveys

Online-only material: color figures

1. INTRODUCTION

It is well understood that the stellar masses of galaxies are better examined with near-IR (NIR) observations compared to shorter wavelengths mainly because the NIR light is relatively less affected by recent episodes of star formation and by internal dust extinction. Moreover, the \(K\)-corrections are also smaller and better constrained in the NIR and hence massive high-redshift objects are relatively prominent in the NIR. Despite this relative insensitivity to luminosity evolution and the effects of dust, the hope of using the NIR counts to constrain the cosmological parameters (Gardner et al. 1993; Moustakas et al. 1997; Huang et al. 2001; Metcalfe et al. 2001) has not proved feasible because evolution in the space density of galaxies was soon understood to be of comparable significance for the NIR counts as the cosmological curvature (Broadhurst et al. 1992).

Disentangling the effects of cosmology from evolution is not straightforward even in the NIR, and now it has become more appropriate to turn the question around and make use of the impressive constraints on the cosmological parameters from WMAP (Spergel et al. 2003), and type Ia supernovae (Riess et al. 1998; Perlmutter et al. 1999), in order to measure more carefully the rate of evolution (Martini 2001; Saracco et al. 2001; Cristóbal-Hornillos et al. 2003; Eliche-Moral et al. 2006). In addition, imaging in the NIR has progressed well with fully cryogenic wide-field imagers now available on several 4 m class telescopes. We also have at our disposal now much better estimates of the luminosity functions of different classes of galaxies from the large local redshift surveys in particular the Sloan Digital Sky Survey (SDSS; Blanton et al. 2003; Nakamura et al. 2003), or Two-Degree Field Galaxy Red Survey (2dFGRS; Cole et al. 2001).

The evolution of the luminosity functions has been addressed making use of spectroscopic redshift surveys. However, the results of those studies differ due to the limitations in terms of low statistic, or small fields probed which lead to uncertainties due to the large-scale structure. In Fontana et al. (2004), a mild (20\%–30\%) evolution in the number density of massive objects since \(z \sim 1\) is found. Also a roughly constant number density for red galaxies to \(z = 0.8\) is found in Im et al. (2002). Using COMBO-17 photometric redshift information (Wolf et al. 2003), and the rest-frame color bimodality at each redshift, Bell et al. (2004) with a sample of \(\sim 25,000\) galaxies, concluded that the stellar mass in red galaxies has increase in a factor 2–3 from \(z \sim 1\) to the present. Combining spectroscopic with photometric redshift data Ilbert et al. (2006) point to an increase in a factor of \(\sim 2.7\) for the density of red bulge-dominated galaxies between \(z = 1\) and \(z = 0.6\). Faber et al. (2007) found a different evolution since \(z \sim 1\) in the number densities in the red
and blue galaxy population, being constant for the blue galaxies, while the number density of the red galaxies increases by a factor of 3. Wide-field imaging with larger covered area, and greater numbers selected to uniform faint limits is complementary to the redshift surveys in examining statistical models proposed for evolution.

In practical terms, it is most useful to combine faint NIR counts with deep blue counts when examining models of evolution to contrast the effects of luminosity and density evolution which affect these two spectral ranges in different ways. In McCracken et al. (2000) and Metcalfe et al. (2001), the authors use nonevolving models with a higher $\phi^*$ normalization in the $B$ band even if this leads to an overprediction of bright galaxies than is observed. Huang et al. (2001) pointed out that both the optical and NIR counts present an excess over the no-evolution models, finding passive evolution models more suitable to match the distributions. The authors emphasize nevertheless their disappointment with the fact that in the passive evolution models the faint number counts are dominated by early-type galaxies, whereas the real data show that spiral and Sd/Irr galaxies are the main contributors to the faint counts even in the $K$ band.

A characteristic feature of the NIR galaxy counts reported in several works (Gardner et al. 1993; Huang et al. 2001; Cristóbal-Hornillos et al. 2003; Iovino et al. 2005) is the change of slope at $17 \leq Ks \leq 18$. This distinctive flattening is not observed in the $B$-band counts. This effect has been interpreted in terms of a change in the dominant galaxy population, becoming increasingly dominated by an intrinsically bluer population (Gardner et al. 1993; Eliche-Moral et al. 2006). In the model described in Cristóbal-Hornillos et al. (2003), a delay in the formation of the bulk of the early-type galaxies to $z_{form} < 2$ and the presence of a dwarf star-forming population are invoked to match the $Ks$-band counts. A similar dwarf star-forming population at $z > 1$, that is not present at lower redshift was found compatible in Metcalfe et al. (1996, 2001) but that work uses a $\phi_0 = 0.5, \Lambda = 0.0$ cosmology, requiring some revision.

Alternatively, an increase of $\phi^*$ for late-type galaxies, driven via mergers, can produce similar results without introducing an ad hoc population that is unseen in the local LFs (Eliche-Moral et al. 2006). In any case, a low $z_{form} \sim 1.5$ for the ellipticals remains necessary to generate a significant decrease in the number of red galaxies and to account for the distinctive break in the NIR count slope at $Ks \sim 17.5$.

Here we use the NIR data from the first completed ALHAMBRA field, hereafter ALH08 (details of the project can be found in Moles et al. (2008) and http://www.iaa.es/almhambra). The limiting magnitudes (at signal-to-noise ratio (S/N)=5 with an aperture diameter of 2 × FWHM) reached in the three NIR bands are in mean for the eight frames in ALH08: $J = 22.6$, $H = 21.5$, and $Ks = 20.1$ with a 0.3 rms (Vega system), and the total area covered amounts to $\sim 0.5$ deg$^2$. The completed survey will cover eight independent fields with a total area of 4 deg$^2$. The ALHAMBRA survey occupies a middle ground in terms of the product of depth and area in all three standard NIR filters. The bright end of the counts is well constrained by our relatively large area allowing a careful examination of the location and size of the break in the count slopes in $J$, $H$, and $Ks$ at fainter magnitudes. We have paid special attention to S/G separation, which at the intermediate magnitude range, is effectively achieved using optical-NIR color indices by combining our ALH08 NIR data with the corresponding Sloan DR5 data.

Unless specified otherwise, all magnitudes here are presented in the Vega system, and the favored cosmological model, with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ was adopted through this paper.

2. OBSERVING STRATEGY AND DATA REDUCTION

The ALHAMBRA survey collects data in 23 optical-NIR filters using the Calar Alto 3.5 m telescope with the cameras LAICA for the 20 optical filters, and OMEGA2000 for the NIR, $JHKs$ filters (Moles et al. 2008; Benítez et al. 2008). In this paper, we discuss the galaxy number counts in the $J$, $H$, and $Ks$ bands computed in the completed ALH08 pointing. Due to the OMEGA2000 and LAICA geometries, two parallel strips of $\sim 1\degree \times 0\degree 25$ are acquired in each of the eight ALHAMBRA fields. Each of these strips is covered by four OMEGA2000 pointings. Figure 1 shows the central part of the processed image for one such pointing in ALH08.

The OMEGA2000 camera has a focal plane array of type HAWAII-2 by Rockwell with 2048 × 2048 pixels. The plate scale is 0.45 arcsec pixel$^{-1}$, giving a full field of view of $\sim 236$ arcmin$^2$. The $JHKs$ images were taken using a dither pattern of 20 positions, with single images time exposures of 80 s in $J$, 60 s in $H$, and 46 s in the $Ks$ band (obtained using respectively 16, 20, and 23 software co-adds). The total exposure time was 5 ks in each of the three filters.

Due to the high quality of raw data images, we have implemented a dedicated reduction pipeline to process the images. This code will be presented and discussed in a forthcoming technical paper. The use of the reduction pipeline guarantees the homogeneity of the process, and allows us to perform a first automatic analysis of the resulting images and to verify the quality of the products in real time. The magnitude at the 50% of recovery efficiency for pointlike sources in the eight final images corresponds in average to $J = 22.4 \pm 0.24$, $H = 21.3 \pm 0.14$, and $Ks = 20.0 \pm 0.13$ in the Vega system. The galaxy number counts have been computed in the high signal-to-noise region of the final images, covering a total of $\sim 1600$ arcmin$^2$, or 0.45 deg$^2$.

2.1. Flat-Fielding and Sky Subtraction

First, the individual images of each observing run were dark subtracted, and flat fielded by super-flat images constructed with the science images in each filter. In the case of NIR imaging, it is specially important to remove properly the high sky level that is changing in short timescales. The sky structure of each image was removed with the XDI Simmons package (Stanford et al. 1995) with a sky image constructed with the median of the six images closest in acquisition time, which in the case of the $J$, $H$, $Ks$ filters correspond to timescales of 480, 360, 276 s, respectively. During this process, cosmic ray masks for each individual image were also created.

SExtractor (Bertin & Arnouts 1996) was used with the preliminary sky-subtracted images to compute the number of detected objects (above a given S/N and with ellipticity lower than a certain limit), and to make a robust estimate of the FWHM of each image. This information together with the sky-level variation was used to automatically remove low-S/N images, lying outside the survey requirements, and also to identify exposures presenting problems such as telescope trailing.

2.2. Ghost and Linear Pattern Masks

The readout of the detector array produces ghost images coming from bright stars. As those spurious effects are replicated in all the readout channels (separated by 128 pixels) of the
Figure 1. Central part (∼ 6.2 × 6.4) of one of the pointings in the ALH08 field in the $K_s$ band.

detector’s quadrant where the real bright source is located, it was possible to mask them before image combination.

Linear patterns produced by moving objects were located in the images using two different approaches: (1) Objects with high ellipticity and pixel area were identified from the individual image SExtractor catalogs. (2) Linear patterns split in multiple spots and structures were located using the Hough transform. Linear patterns detected by any of the two methods were masked.

2.3. Image Combination

Using XDIMSUM, the images were combined masking the cosmic rays, bad pixels and linear patterns. Those preliminary co-added images were used to create object and bright cores masks. Object masks were used to cover the sources in the second iteration of the XDIMSUM sky subtraction procedure. Bright cores masks operate when constructing an improved version of the cosmic ray masks.

At this point, the individual images have been dark current corrected, flat fielded, and sky subtracted. Each individual image has an associated mask containing the bad pixels, cosmic rays, linear patterns, and ghost images.

To perform the final combination of the processed images we used SWARP (Bertin et al. 2002), a code that combines the images, correcting at the same time the geometrical distortions in the individual images using the information stored in WCS headers. The astrometric calibration of each individual image and the update of its WCS headers was done by the pipeline using an automatic module. During the SWARP combination, the extinction variations among the images were also corrected. More technical details on the image combination are given in the Appendix.

2.4. Photometric Calibration

For the photometric calibration we used the Two Micron All Sky Survey (2MASS) catalogs (Cutri et al. 2003). After having combined all the images of each pointing, the objects in common with the 2MASS catalogs were found and those with higher S/N selected to compute a zero-point offset.

In Figure 2, an example of the photometric calibration for one of the pointings in ALH08 is shown. The histogram with the rms in the photometric calibration for the ALH08 pointings in the three NIR bands is shown in Figure 3. The mean value for the rms is 0.028 ± 0.006 mag, and a mean of 36 calibration sources have been used in each frame. We have not found any appreciable color related trend.

The calibrated images were inspected for the possible presence of ring patterns that would have been produced by pupil ghosts. We computed for each band, and for all the sources used in the calibration process of the different final frames, the difference between our photometry and the 2MASS photometry as a function of the radial distance to the nominal field center.

We found a significant effect, over 0.02 mag only in the $J$-band images, as is shown in Figure 4. This effect was corrected by fitting the pupil ghost, using the mscpupil task in the IRAF MSCRED package (Valdes 2002), and removing this pupil image from the flat fields and individual images. The final resulting radial differences are shown for the $J$ band in Figure 5 where it clearly appears that all the systematics were corrected well below the 1σ level.

3. GALAXY NUMBER COUNTS

The steps to compute robust counts to the 50% detection level of the images are similar to those described in Cristóbal-
Hornillos et al. (2003) and in Eliche-Moral et al. (2006). In the next section, we detail how the best set of SExtractor parameters was estimated as a compromise between optimizing the depth at the 50% completeness level while the number of spurious sources keeping low.

3.1. Completeness Corrections

In order to compute the corrections that should be applied to the faint part of the galaxy counts we have performed a set of Monte Carlo simulations where real sources from the images were injected back to the same science image at different positions. The completeness correction to be applied depends on the surface brightness profile of the source. To account for this we computed a different correction function for sources in three effective radius (Re) intervals. Those Re intervals in pixels for the simulations were chosen from the histogram of the Figure 6 (top panel): Re ≤ 1.75, 1.75 < Re ≤ 2.25, and Re > 2.25. In Figure 6 (bottom panel), it is shown how the Re recovered decreases as the magnitude goes fainter (see below for a description of how these values were obtained).
Figure 6. Top panel: histogram of Re for the sources in one of the pointings of the field ALH08. Bottom panel: differences between Re(in) and Re(out) for the dimmed injected sources. The symbols correspond to × Re(in) ≤ 1.75 pixels, □ 1.75 < Re(in) ≤ 2.25 and △ Re(in) > 2.25 pixels. The shaded is the range of magnitudes between the 50% and the 80% of detection efficiency.

Figure 7. Completeness correction for the same pointing of the previous figures in the J band using 0.8σ DETECT_THRESH and the 2.5 pixel Gaussian kernel. The vertical dotted (solid) lines are the magnitude at the 50% (80%) of detection efficiency.

Figure 8. Top panel: 50% vs. 80% of recovering efficiency for the same pointing as before in the Ks band using different SExtractor detection strategies. The size in pixels of the SExtractor Gaussian convolution kernel is given in the labels. The detection thresholds are indicated at the points. Bottom panel: 50% of detection efficiency vs. spurious to total ratio.

data. As a validation of the procedure, the same simulations have been performed using real NICMOS F110W sources from the HDF-S Flanking Fields. The NICMOS images were resampled and convolved with a suitable Gaussian kernel to match the pixel scale and FWHM of the OMEGA2000 image under study. Initial sources were taken in the interval \([m - 1, m + 1]\) (\(m\) being the magnitude under study), which produces a realistic \(m - R_e\) relation. As can be seen from Figure 7, the results in the completeness correction are the same that using dimmed sources from the image.

In the top panel of Figure 8, we show the depth to the 50% and 80% of recovering efficiency, computed using a linear interpolation in the magnitude versus efficiency data. The figure indicates that a decreasing of the detection thresholds, in order to get a fainter level at the 50% of recovery efficiency limit, will not improve by much the limit at the 80% of completeness, which seems to reach a plateau. Moreover, as will be seen from the reliability plots, it produces a significant increase of detected spurious sources, as we explain below.

3.2. Detection Reliability

To accurately compute the galaxy number counts it is important to establish the reliability of the detections at the faint magnitude end. To find out the optimum way to evaluate that reliability we have studied the performance of three different...
methods. The first approach was to create artificial sky images with the same rms and background distribution than the real ones. The ratio of spurious versus real detections was computed running SExtractor over the science and the artificial sky images.

We have also inspected the performance of the method used in Cristóbal-Hornillos et al. (2003). Basically half exposure time images were created from two complementary sets of the data. The detections were performed in the total time image and the source fluxes measured in the half-time images using the SExtractor double image mode for the same automatic apertures. Those created sources showing a magnitude difference greater than $3\sigma$ were considered spurious.

The last method and the one that, at the end, produces the best results, consisted in constructing sky images using a similar combination procedure that used to create the science images: combining the unregistered processed images with subtracted background using an artificial dither pattern. The major difficulty here was to remove the extended sources that could bias the sky even when doing trimmed mean (discarding 20% of the pixels at each side). We have confirmed that SExtractor does locate these smooth deviations over the sky rms when filtering is used. To avoid this we multiplied those sky images by $-1$ and used them as real sky images.

In Figure 9, we show a comparison between the spurious rate at the 50% of detection efficiency computed over the “real sky” and the artificial sky. A good agreement between both methods is observed, indicating that the use of artificial images to compute the ratio of spurious to total detections is adequate. Being artificial images faster to construct we made use of them to estimate the detection reliability in each pointing.

The bottom panel of Figure 8 shows the magnitude reached at the 50% of detection efficiency versus the spurious to total ratio at the same magnitude bin. From the figure we can see that in order to reach a deep 50% detection limiting magnitude, maintaining at the same time the number of spurious detections below 20%, the optimum SExtractor DETECT_THRESH-FILTER combinations are DETECT_THRESH = 1.2 or 1.4 without filtering, or DETECT_THRESH = 0.8 using a filtering with a Gaussian kernel of size similar to the image FWHM. In the top panel of Figure 8, it is shown that those combinations reach roughly the same magnitude at the 80% of recovery efficiency. We have decided to use the latter filter-

DETECT_THRESH combination because, as can be outlined from the bottom panel in Figure 10, the differences between the input and the recovered AUTO magnitudes in the simulations are close to zero in all the magnitude range up to the magnitude at the 80% of recovery efficiency. Close to the magnitude at the 50% of completeness the recovered magnitude appears to be $0.1-0.2$ mag brighter than in the previous bin. This effect could be due to the fact that only those sources that suffer from noise brightening were found by SExtractor and used to compute the input–output magnitude differences, producing a bias toward brighter recovered objects. Following those results, the number counts in the following sections will be computed and corrected up to the magnitude of 80% of recovery efficiency for pointlike sources, avoiding any possible systematics due to a magnitude shift at the 50% completeness bin.

As pointed before, the photometry of the sources was obtained using MAG_AUTO. Simulations indicate no significant differences between simulated and recovered magnitudes (at the 80% recovery efficiency) for the used values of the SExtractor parameters FILTER and DETECT_THRESH. Using the
same kind of simulations we computed the rms of the recovered MAG_AUTO values in each bin to characterize the photometric error, the results are shown in Figure 11.

### 3.3. Star-Galaxy Separation

In Cristóbal-Hornillos et al. (2003), it was shown that fainter than \( Ks = 17.0 \) the correction due to stars is < 0.06 dex. However, given the lower Galactic latitude of the ALH08 field, a higher number of contaminating stars are expected. A correct star subtraction is relevant in the intermediate magnitude range. At bright magnitudes, stars can easily be separated from galaxies using a compactness criterium. In contrast, at intermediate magnitudes the star/galaxy separation is more demanding because many galaxies are barely resolved with small apparent sizes compared with the FWHM and pixel resolution, as can be seen from the diagram shown in Figure 12.

The viability of star/galaxy separation using the SExtractor neural network has also been analyzed. For this purpose, using the same Monte Carlo method explained before, bright stars and galaxies from the images have been artificially dimmed to each magnitude bin and their SExtractor stellarity parameter recovered. In Figure 13, it clearly appears how, in one final frame with FWHM = 1.1, the input and recovered CLASS_STAR differences are less than 0.1 up to \( Ks = 18.0 \). But, in the next bin \( Ks > 18.5 \), the CLASS_STAR of the dimmed stars and galaxies could lead to some misclassification. Nevertheless, as can be seen from the histogram in the bottom panel of Figure 13, a non-negligible number of objects start populating the range from 0.4 to 0.8 in CLASS_STAR at magnitudes fainter than 17 in \( Ks \), and the selection of the CLASS_STAR cutoff might bias the star counts estimates.

An alternative way to perform the star/galaxy separation makes use simply of color–color diagrams. Huang et al. (1997) have established a reliable star/galaxy separation using the \( B-I \) versus \( I-K \) colors. Here we make use of the SDSS DR5 data for the ALH08 field to proceed with this separation using the \( g-r \) versus \( J-Ks \) colors shown in Figure 14. The star counts are corrected by the ratio of the Sloan/Alhambra completeness factors in the corresponding filter shown in Figure 15. The star counts using Sloan-Alhambra colors were computed to magnitudes 19.5, 18.5, and 18.0 respectively in the \( J, H, \) and \( Ks \) bands, where the Sloan/Alhambra completeness is > 0.5. For

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**Figure 11.** Median photometric random errors in magnitudes per magnitude bin (\( \sigma_m \)) in the three NIR filters for the eight ALH08 pointings (crosses and dotted lines); the three lines represent sources with \( Re < 1.75, 1.75 < Re < 2.25, \) and \( Re > 2.25 \) pixels. The magnitude errors are computed as the rms of the recovered sources magnitudes in each bin of the simulations described in the text. Error bars represent the rms of the computed \( \sigma_m \) among the pointings. Exponential grow fit (\( \sigma(m) = \sigma_0 + a \exp [b(m - m_0)] \)) to the magnitude errors in each band (solid lines).

**Figure 12.** Peak/ISOPHOTAL_AREA vs. \( Ks \) diagram. The red dots are object for which the SExtractor stellarity index is greater than 0.8. (A color version of this figure is available in the online journal.)

**Figure 13.** Top panel: CLASS_STAR input-output differences as a function of input artificially dimmed magnitude for a set of well defined stars (CLASS_STAR(in) \( \sim 1 \)) and galaxies (CLASS_STAR(in) \( \sim 0 \)). In the case of stars, \( 1-(\text{CLASS}_{\text{STAR(out)}}-\text{CLASS}_{\text{STAR(in)}}) \) is plotted. Bottom panel: histogram of CLASS_STAR for different ranges in the \( Ks \) magnitudes.
Figure 14. $g-r$ vs. $J-K_s$ plot used to perform the star–galaxy separation. All objects in ALH08 with $S/N > 5$ are plotted. The line separating the two classes is $g-r = 1.2 + 2.0 \cdot (J-K_s)_{AB}$. The plotted symbols correspond to the Sloan classification dots for representing stars and the crosses for galaxies. Redshift-color tracks for three galaxy models constructed using the Bruzual & Charlot (2003) code are shown. The redshift values are displayed over the single stellar population (SSP) track, the marks over the other two curves have the same redshift spacing. The diamonds represent the mid-stellar locus given in Covey et al. (2007). Two contour lines containing the 95% and the 68% are displayed for the galaxies and stars using the Sloan classification.

The fainter star counts we used a 0-slope extrapolation where the models of star counts in the Galaxy are flatter (see Figure 16).

In Figure 15, bottom panel, the correction to the log($N$) galaxy counts is presented, showing that fainter than the magnitudes up to where the color–color separation could be performed the correction in the three bands is $< 0.08$ dex.

To check the validity of the star counts computed using the color–color approach, those are compared with the Robin et al. (1996) Galactic star counts models in Figure 16. The lines correspond to star counts in the Galaxy for galactic coordinates ($l = 100, b = -45$), very close to the coordinates of the ALH08 field ($l = 99, b = -44$). From this figure, it appears that it is possible to accurately remove the stars from the galaxy counts using the color–color diagram. This was the method we have finally used to do the star/galaxy separation.

Finally, it is noteworthy to mention that star/galaxy separation will be done more accurately when the photometry in the 23 Alhambra bands is available, as the system will provide a sort of low-resolution spectroscopy for each object.

4. RESULTS

The corrected galaxy number counts have been computed for the ALH08 field in the three standard NIR filters in a consistent way in the sense that they have been estimated following the same scheme for the three bands. The number count data, computed and corrected up to the magnitude of 80% of recovery efficiency for pointlike sources, are presented in the Tables 1–3.

The error in the number counts for each pointings is the sum in quadrature of the rms in the estimation of the completeness corrections, with the contribution of Poisson noise and galaxy clustering calculated for each magnitude bin following Equation (1) (Huang et al. 1997), that includes the angular correlation function

$$\sigma_i^2 = N_i(m) + 5.3 \left( \frac{r_0}{r_*} \right) Q_i^{1-\gamma}/2 N_i^2(m),$$

with $N_i$ being the raw counts in the pointing, $r_0 = 7.1$ Mpc, $\gamma = 1.77$, and $5 \log(r_*) = m - M_* - 25$. $M_*$ is set to $-22.95$, $-23.69$, and $-23.93$ for the $J$, $H$, and $K_s$ filters. The final uncertainty in the combined counts per square degree and
observations. Calculated following the Las Campanas Infrared Survey (LCIRS; Chen et al. 2002) et al. (1998) and Metcalfe et al. (2006), obtained from NICMOS Frith et al. (2006). However, the faint end (Moy et al. 2003), and the systematic of 0.28 mag. This offset was applied an offset of 0.215 mag. In Figures 17–19, the Alhambra counts in the J H band galaxy counts at magnitudes J > 21.5.

The Alhambra counts in the H band are in good correspondence with the published data by Martini (2001); Frith et al. (2006) and with the bright part of the data from Moy et al. (2003), after applying an offset of −0.215 mag. This offset was calculated following the −0.065 calibration difference among Las Campanas Infrared Survey (LCIRS; Chen et al. 2002) reported in Moy et al. (2003), and the systematic of −0.28 mag difference between LCIRS and 2MASS magnitudes reported in Frith et al. (2006). However, the faint end (H > 20) of our data is significantly above the faint number count data from Yan et al. (1998) and Metcalfe et al. (2006), obtained from NICMOS observations.

Regarding the Ks filter, for which there are numerous number count studies, our galaxy counts are in good agreement with most of the published data, as can be appreciated in Figure 19.

4.1. The Measured Slopes

We have found, as in previous studies, that the slope of the galaxy number counts displays a clear change at Ks ∼ 17.3 (see Figure 20). However, in the present work we also have found this change of slope in the J H band galaxy counts at J ∼ 19.1 and H ∼ 18.2.

The slopes of the bright end and faint end counts in the different bands were measured using the least-squares method. The values that we have calculated and the magnitude ranges used for the fits are listed in Table 4. The results show that the faint slopes for the three NIR filters are the same within 2σ, whereas the bright slope is steeper in the Ks band.

As is described in Teerikorpi (2004) the fact that the photometric error increases at fainter magnitudes, and that the differential galaxy number counts also rises toward lower fluxes, lead to a steeper observed slope at the faint end. This effect is related to the Eddington bias (Eddington 1913). To investigate if the computed magnitude errors could bias our slope estimates we have done the following study. First, in each filter we use the exponential grow function fit to the magnitude errors (Figure 11). Then we extended our computed number counts 1 mag fainter using the corresponding slope in Table 4, simulating a Gaussian decay for fainter magnitudes. The parameter σ for the Gaussian is the value of the exponential fit to the error

| Magnitude | Raw Counts | Effective Correction | log(Nc) | log(Nc*) | Area |
|----------|------------|----------------------|---------|----------|------|
| 13.00    | 43.0       | 1.00                 | 1.31±0.49 | 1.30±0.73 | 0.441 |
| 13.50    | 31.0       | 1.00                 | 0.92±0.92 | 0.95±0.96 | 0.441 |
| 14.00    | 53.0       | 1.00                 | 1.13±0.66 | 1.08±0.90 | 0.441 |
| 14.50    | 75.0       | 1.00                 | 1.63±0.36 | 1.64±0.61 | 0.441 |
| 15.00    | 118.0      | 1.00                 | 1.88±0.28 | 1.89±0.49 | 0.441 |
| 15.50    | 129.0      | 1.00                 | 2.00±0.54 | 2.00±0.41 | 0.441 |
| 16.00    | 175.0      | 1.00                 | 2.11±0.22 | 2.11±0.34 | 0.441 |
| 16.50    | 242.0      | 1.00                 | 2.55±0.10 | 2.56±0.24 | 0.441 |
| 17.00    | 309.0      | 1.00                 | 2.77±0.07 | 2.77±0.15 | 0.441 |
| 17.50    | 436.0      | 1.00                 | 2.91±0.07 | 2.91±0.09 | 0.441 |
| 18.00    | 634.0      | 1.00                 | 3.22±0.04 | 3.22±0.11 | 0.441 |
| 18.50    | 832.0      | 1.00                 | 3.40±0.03 | 3.40±0.09 | 0.441 |
| 19.00    | 1128.0     | 1.07                 | 3.63±0.02 | 3.64±0.06 | 0.441 |
| 19.50    | 1615.0     | 1.08                 | 3.80±0.02 | 3.80±0.05 | 0.441 |
| 20.00    | 2303.0     | 1.09                 | 3.99±0.08 | 3.99±0.10 | 0.441 |
| 20.50    | 3285.0     | 1.12                 | 4.18±0.04 | 4.18±0.06 | 0.441 |
| 21.00    | 4455.0     | 1.17                 | 4.34±0.03 | 4.34±0.05 | 0.441 |
| 21.50    | 5030.0     | 1.25                 | 4.50±0.02 | 4.50±0.03 | 0.381 |
| 22.00    | 1739.0     | 1.52                 | 4.67±0.03 | 4.67±0.02 | 0.109 |

Notes.

a Raw counts including stars.

b Effective correction, defined as (Nc + Nct)/2 - area - raw.

c Corrected galaxy counts errors corresponds to the Poissonian and galaxy clustering uncertainty plus error in completeness added in quadrature.

d Mean of the eight pointings and its rms.

magnitude is given by

\[ \sigma(m) = \sqrt{\frac{\sum \sigma_i^2}{\Omega \Delta m}}. \] (2)
values for pointlike sources at 1 magnitude fainter that the last bin given in Tables 1–3 ($\sigma = 0.35, 0.41, \text{ and } 0.44$ at respectively $J = 23.0, H = 22.0, \text{ and } K s = 21.0$). Using the fitted magnitude errors for pointlike objects ($\sigma(m)$), and assuming that real distribution is close to the extended number counts ($N(m)$), we simulate the bias produced by the photometric error on the observed counts, by convolving the $N(m)$ with $\sigma(m)$ using Equation (3). The results indicate an increase in the slope less than 0.015 in the case of $J$ and $H$ filters, and 0.03 in the $K s$ band, meaning that the original distributions would have a faint end slope of 0.33, 0.34, and 0.30 in the $J$, $H$, and $K s$ filters in the ranges given in Table 4.

$$N(m_{\text{obs}}) = \int N(m) \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(m-m_0)^2}{2\sigma^2}} dm.$$  

(3)

The increase of the slope is not observed when we simulate this bias directly over the observed count distribution. This is due to the fact that fainter than the 80% completeness magnitude bin there is a fast decrease of the number of detected sources, and that in this bin the typical photometric error ($\sigma_m = 0.23-0.26$) for the dominant pointlike sources, cause the bias to not significantly affect the previous bins. In this case, the slopes after applying the bias are lower than the computed from the observed number counts (0.33±0.01, 0.33±0.02, and 0.30±0.02 in $J$, $H$, and $K s$). This result would suggest that the original distribution slopes at the faint end would be higher than those given in Table 4. We have used the combined results from this paragraph and the previous one to increase the uncertainty in the slope, leaving the values computed directly from the observed number counts as satisfactory estimates of the real distribution slope at the faint end.

Our results for the $K s$ band are in good agreement with other $K$-band surveys which also report a similar change of slope in the galaxy counts in the range 17.0–18.0 (Daddi et al. 2000; Huang et al. 2001; Cristóbal-Hornillos et al. 2003; Iovino et al. 2005). At the bright part our slopes are close to the values measured in Kümml & Wagner (2000), Martini (2001), Cristóbal-Hornillos et al. (2003) and Iovino et al. (2005; see Table 5), while other references point to a steeper bright slope (Gardner et al. 1993, 1996; Huang et al. 1997, 2001). This could be due to the fact that the last authors could extend the power-law fit to brighter magnitudes due to their larger surveyed area, whereas our fit is closer to the magnitude where the break is found which would lead to a decrease in the slope if the break transition is smooth. In the faint part of the $K s$ counts, a slope of 0.33 found in this work is in agreement with Bershady et al. (1998), Huang et al. (2001) and Imai et al. (2007). The value of the faint slope from the ALHAMBRA data is however steeper than the value reported in some surveys covering smaller areas, where the fitted range extends to fainter magnitudes (Gardner et al. 1993; Moustakas et al. 1997; Maihara et al. 2001). Here the differences might be due to cosmic variance. A larger than 2σ disagreement is found with the faint slope of Cristóbal-Hornillos et al. (2003) fitted in the range [17.5,19.5], although their value increases to 0.29 when the fit interval is extended to $K s = 21.0$. Kümml &
Table 3
Corrected Galaxy Number Counts in the $K_s$ Band

| Magnitude | Raw Counts$^a$ | Effective Correction$^b$ | log($Nc$)$^c$ | log($Nm$)$^d$ | Area |
|-----------|---------------|------------------------|-----------|-----------|------|
|           |               |                        | (deg$^{-2}$) | (deg$^{-2}$) |      |
| 12.00     | 25.0          | 1.00                   | 1.14$^{+0.54}_{-1.14}$ | 1.13$^{+0.74}_{-1.13}$ | 0.440 |
| 12.50     | 44.0          | 1.00                   | 1.61$^{+0.32}_{-1.61}$ | 1.60$^{+0.52}_{-1.60}$ | 0.440 |
| 13.00     | 41.0          | 1.00                   | ...         | ...         | 0.440 |
| 13.50     | 78.0          | 1.00                   | 1.89$^{+0.24}_{-0.55}$ | 1.90$^{+0.32}_{-0.90}$ | 0.440 |
| 14.00     | 101.0         | 1.00                   | 2.03$^{+0.20}_{-0.20}$ | 2.03$^{+0.37}_{-0.20}$ | 0.440 |
| 14.50     | 141.0         | 1.00                   | 2.21$^{+0.16}_{-0.26}$ | 2.22$^{+0.30}_{-0.22}$ | 0.440 |
| 15.00     | 188.0         | 1.00                   | 2.41$^{+0.12}_{-0.17}$ | 2.41$^{+0.36}_{-0.13}$ | 0.440 |
| 15.50     | 291.0         | 1.00                   | 2.74$^{+0.07}_{-0.09}$ | 2.74$^{+0.14}_{-0.21}$ | 0.440 |
| 16.00     | 375.0         | 1.00                   | 2.96$^{+0.05}_{-0.06}$ | 2.95$^{+0.11}_{-0.15}$ | 0.440 |
| 16.50     | 585.0         | 1.00                   | 3.22$^{+0.03}_{-0.04}$ | 3.28$^{+0.08}_{-0.09}$ | 0.440 |
| 17.00     | 940.0         | 1.00                   | 3.49$^{+0.02}_{-0.02}$ | 3.49$^{+0.06}_{-0.07}$ | 0.440 |
| 17.50     | 1307.0        | 1.03                   | 3.67$^{+0.02}_{-0.02}$ | 3.67$^{+0.05}_{-0.06}$ | 0.440 |
| 18.00     | 1836.0        | 1.04                   | 3.86$^{+0.07}_{-0.06}$ | 3.86$^{+0.07}_{-0.07}$ | 0.440 |
| 18.50     | 2614.0        | 1.05                   | 4.04$^{+0.05}_{-0.06}$ | 4.04$^{+0.07}_{-0.08}$ | 0.440 |
| 19.00     | 3698.0        | 1.11                   | 4.24$^{+0.04}_{-0.04}$ | 4.24$^{+0.06}_{-0.07}$ | 0.440 |
| 19.50     | 4477.0        | 1.37                   | 4.42$^{+0.03}_{-0.03}$ | 4.42$^{+0.04}_{-0.04}$ | 0.440 |
| 20.00     | 574.0         | 1.55                   | 4.50$^{+0.04}_{-0.05}$ | 4.50$^{+0.02}_{-0.02}$ | 0.054 |

Notes.
$^a$ Raw counts including stars.
$^b$ Effective correction, defined as $(Nc + N_{st})/(2 \cdot \text{area} \cdot \text{raw})$.
$^c$ Corrected galaxy counts, errors correspond to the Poissonian and galaxy clustering uncertainty plus error in completeness added in quadrature.
$^d$ Mean of the eight pointings and its rms.

Figure 17. Galaxy number counts in the $J$ filter compared with data from other surveys. The lines correspond to the number counts models in Cristóbal-Hornillos et al. (2003) and Eliche-Moral et al. (2006) described in the text.

(A color version of this figure is available in the online journal.)

Wagner (2000) give a higher value for the faint slope; however, due to the brighter limiting magnitude of their number counts they could  established a break or the beginning of a rollover in the interval $K_s = [16.5,17.0]$. In the $H$ and $J$ bands there are fewer works reporting countslope values. Our results, given in Table 4, show similar slopes for the $J$ and $H$ filter at the bright and faint ends. As can be seen in Tables 6 and 7 our result at the bright end are in good agreement with the bright-end slope values to $H = 19$ given in Martini (2001) and Chen et al. (2002), and in the $J$ filter with the results in Väisänen et al. (2000) and Iovino et al. (2005). At the faint end, only the slope values in Maihara et al. (2001) in the $J$
Figure 18. Galaxy number counts in the $H$ filter compared with data from other surveys and the models in Cristóbal-Hornillos et al. (2003) and Eliche-Moral et al. (2006) described in the text.

(A color version of this figure is available in the online journal.)

Figure 19. Galaxy number counts in the $K_s$ filter compared with data from the literature and the galaxy counts models in Cristóbal-Hornillos et al. (2003) and Eliche-Moral et al. (2006) described in the text. A model where only the passive evolution of stellar populations is considered (PLE) is also shown.

(A color version of this figure is available in the online journal.)

5. COMPARISON WITH MODELS OF EVOLUTION

Historically, the galaxy number counts have been used to examine parameters of the cosmological model and to test different galaxy evolution scenarios. Now that the cosmological parameters are fixed using other methods the consequences derived from the galaxy counts for the galaxy evolution have become more precise. The ALHAMBRA computed counts in the three NIR bands provide a good data set which, when combined with other optical data and independent determinations of the local luminosity functions, allow evolution to be examined, in particular the still uncertain question of the formation and evolutionary history of early type galaxies.

In this section, we compare our counts with semianalytic predictions from number-count models, following the recipes given in Gardner (1998), which trace back the redshift evolution of the galaxy spectral energy distribution (SED) of different galaxy classes. The SEDs have been computed using the codes of Bruzual & Charlot (2003). We apply dust attenuation following Eliche-Moral et al. (2006), $\tau_B = 0.6$ that corresponds to $\tau_V = 0.4$ if the attenuation follows a $\propto \lambda^{-2}$ power law. We apply dust extinction either directly and by the same amount to all the galaxies using Bruzual & Charlot (2003) codes, following the prescription given in Charlot & Fall (2000), or by using the luminosity-dependent extinction law proposed in Wang (1991). The parameters we use to characterize four different galaxy types are given in Table 8. In the LF parameterization for the different bands, $M^*$ is changed according to the rest-frame colors of the evolved SED (from $z_f$ filter, estimated in an area of 4 arcsec$^2$, and Chen et al. (2002) have a significant discrepancy.
to $z = 0$), whereas $\alpha$ and $\phi^*$ are assumed to be the same in all filters.

In the first step, we compare the ALHAMBRA NIR counts with the prediction obtained using the model proposed in Cristóbal-Hornillos et al. (2003). The extinction correction was applied directly to the SEDs, as an entry parameter in the code described in Bruzual & Charlot (2003) using $\tau_V = 1.2$ for stars younger than $10^7$ yr, and $\mu = 0.3$ as the fraction of it coming from an ambient contribution which affects the old stars too. The parameters used in the local luminosity function are $M^* = -24.07$, $\alpha = -1.00$, $\phi^* = 4.94 \times 10^{-3}$ calculated in Gardner et al. (1997; Cole et al. 2001 provide the parameters for the $\Lambda$-cosmology), which were transformed to take into account the presence of different galactic types in the local LF adopting the galaxy mixing $E/S0 = 28\%$, Sab/Sbc = 47\%, Scd = 13\%.

The model also adds a dwarf star-forming population, characterized by a stellar population of age 1 Gyr at all redshifts, and a steeper slope LF ($M^* = -23.12$, $\alpha = -1.5$, $\phi^* = 0.96 \times 10^{-3}$) given in Gardner (1998). The formation redshifts are $z_f = 2.0$ for the E/S0 and intermediate-type disk galaxies and $z_f = 1.0$ for the Scd, although the formation redshift for the Scd could be $z_f = 4.0$ or higher without modifying the total counts in NIR, that at magnitudes fainter than $K_s = 21.5$ are dominated by the dwarf star-forming population. Due to the disappearance of the red-galaxy population at $z > 2.0$ this model reproduces the change of slope in the $K_s$ band observed in the present data (see Figure 19).

However, as it was discussed in Eliche-Moral et al. (2006), this model fails to simultaneously reproduce the blue band counts as can be seen in Figure 21, where the predicted counts are compared with some $B$-band galaxy counts from the literature.

The number-count models that we consider now, below, include some modifications which aim to simultaneously reproduce the counts in both the NIR filters and blue filters. For these, the local-type-dependent luminosity functions were computed from Sloan data in Nakamura et al. (2003), as shown in Table 9.

We consider first the two models proposed in Eliche-Moral et al. (2006). In the first model, a $\phi^*$ evolution $\propto (1 + z)^2$, driven via mergers, is considered for the spiral and irregular galaxies. This evolution in $\phi^*$ is compensated by the evolution in $M^*$ to conserve the luminosity density. Is it important to take in mind that these models calculate the galaxy number counts tracing back the evolution of the stellar populations to $z = 0$, so the intrinsic brightening with $z$ of the stellar populations must be added to the $M^*$ evolution when it is compared with luminosity functions computed at higher redshifts. The formation redshift for the majority of the ellipticals and intermediate-type disk galaxies in this model was set to 1.5. In the second model, the low formation redshift for the early spiral galaxies could be set to $z_f = 4$, avoiding at the same time an unreasonable high number of late-type galaxies at high-$z$, using the merger parameterization $\phi^* \propto \exp[-Q/\beta((1 + z)^{-\beta} - 1)]$ given in Broadhurst et al. (1992). The value of $\beta = 1 + (2q_0)_{0.05}/2$ was set to 1.53 using $q_0 = -0.55$. A value of $Q = 1$ was used as in Eliche-Moral et al. (2006). The extinction correction, which is important in the blue bands, was set to $\tau_B = 0.6$ with the prescription given in Wang (1991). As is shown in Figures 17 and 18 these two models that fit the $B$ (Figure 21) and $K_s$ (Figure 19) galaxy counts overestimate the slope variation at $J \sim 19$ in the Alhambra counts, and at $H \sim 18$ in data from other surveys.

In order to explain the change of slope in the NIR galaxy counts, the population of red elliptical galaxies has to decrease

![Figure 20](image-url) Galaxy number count bright and faint slopes found in this work. Error bars are the Poissonian and galaxy clustering uncertainty added in quadrature with the rms in the estimation of the completeness corrections.

### Table 4

| Filter | Bright Range | Bright Slope | Faint Range | Faint Slope |
|--------|--------------|--------------|-------------|-------------|
| $J$    | [17.0,18.5]  | 0.44 ± 0.04  | [19.5,22.0] | 0.34 ± 0.01 |
| $H$    | [15.5,18.0]  | 0.46 ± 0.02  | [19.0,21.0] | 0.36 ± 0.02 |
| $K_s$  | [15.0,17.0]  | 0.53 ± 0.02  | [18.0,20.0] | 0.33 ± 0.03 |
with the redshift. Although a model taking into account only the stellar evolution with look-back time fits the blue band counts (see Figure 21), this model overpredicts the faint counts in the NIR bands as can be seen in Figure 19. Due to the red color of the slope change only the elliptical population parameterized with a short burst of star formation can play this role. Figure 22 shows the evolution with redshift of the $J-H$ and $J-K_s$ colors for an elliptical galaxy and an early spiral formed at $z = 4$ (with stellar populations according to the parameters in Table 8, and reddening in the spectra applied directly from the Bruzual & Charlot (2003) code using $\tau_V = 0.8$ and $\mu = 0.5$). The estimated colors of the slope change from the fits given in

Table 5

| Reference      | Surveyed Area (arcmin$^2$) | Limit Magnitude | Bright Range | Bright Slope | Faint Range | Faint Slope | Filter |
|----------------|----------------------------|-----------------|--------------|--------------|-------------|-------------|--------|
| Gardner93      | 5688                       | 14.5            | [10.0,16.0]  | 0.67         | [18.0,23.0] | 0.23        | K’     |
| Gardner93      | 582                        | 16.75           | ...          | ...          | ...         | ...         | ...    |
| Gardner93      | 167.7                      | 18.75           | ...          | ...          | ...         | ...         | ...    |
| Gardner93      | 16.5                       | 22.5            | ...          | ...          | ...         | ...         | ...    |
| Glazebrook94   | 552                        | 16.5            | ...          | ...          | ...         | ...         | ...    |
| Djorgovski95   | 3                          | 23.5            | ...          | ...          | ...         | ...         | ...    |
| McLeod95       | 22.5,2.0                   | 19.5,21.25      | ...          | ...          | ...         | ...         | ...    |
| Gardner96      | 35424                      | 15.75           | <16.0        | 0.63 ± 0.01  | ...         | ...         | ...    |
| Moustakas97    | 167.7                      | 18.75           | ...          | ...          | [18.0,23.0] | 0.23 ± 0.02 | K      |
| Huang97        | 29628                      | 16.0            | ...          | ...          | ...         | ...         | ...    |
| Minezaki98     | 181,2.21                   | 19.1,21.2,2       | ...          | ...          | ...         | ...         | ...    |
| Bershady98     | 1.5                        | 24.00           | ...          | ...          | >18.5       | 0.36        | K      |
| Szokoly98      | 2185                       | 16.5            | [14.5,16.5]  | 0.50 ± 0.03  | ...         | ...         | Ks     |
| Saracco099     | 20                         | 22.25           | ...          | ...          | [17.25,22.5] | 0.38        | Ks     |
| Vaisinon00     | 3492.2088                  | 16.75,17.75     | [15.0,18.0]  | 0.40-0.45    | ...         | ...         | K      |
| Martin01       | 180.51                     | 17.0,18.0       | [14.0,18.0]  | 0.54         | ...         | ...         | K      |
| Daddio00       | 701.447                    | 18.5,19.0,0      | [14.0,17.5]  | 0.53±0.02    | >17.5       | 0.32±0.02   | Ks     |
| Kuncme00       | 3348                       | 17.25           | [10.5,17.0]  | 0.56±0.01    | [16.5,17.5] | 0.41        | K      |
| Malhar01       | 4                          | 25.25           | ...          | ...          | >20.1       | 0.23        | K’     |
| Saracco01      | 13.6                       | 22.75           | ...          | ...          | >19         | 0.28        | Ks     |
| Huang01        | 720                        | 19.5            | <16.5        | 0.64         | >17         | 0.36        | K’     |
| Cimatti02      | 52                         | 19.75           | ...          | ...          | ...         | ...         | ...    |
| Cristobal03    | 180.50                     | 20.0,21.0       | [15.5,17.5]  | 0.54         | [17.5,19.5] | 0.25        | Ks     |
| Iovino05       | 414                        | 20.75           | [15.75,18.0] | 0.47±0.23    | [18.0,21.25] | 0.29±0.08   | Ks     |
| Elston06       | 25560                      | 19.25           | ...          | ...          | ...         | ...         | ...    |
| Imai07         | 750,306                    | 18.625,19.375   | <18.00       | 0.32±0.06    | >19.00      | 0.32±0.06   | Ks     |
| Feulner07      | 925                        | 20.75           | ...          | ...          | ...         | ...         | ...    |
| This work      | 1584,194                   | 19.5,20.0       | [15.0,17.0]  | 0.53±0.02    | [18.0,20.0] | 0.33±0.03   | Ks     |

Notes.

a 3σ limit for point sources.
b 50% efficiency for point objects.
c The latest magnitude bin in the number counts.
d 80% efficiency for point objects.

Table 6

| Reference      | Surveyed Area (arcmin$^2$) | Limit Magnitude | Bright Range | Bright Slope | Faint Range | Faint Slope | Filter |
|----------------|----------------------------|-----------------|--------------|--------------|-------------|-------------|--------|
| Bershady98     | 1.5                        | 24.5            | ...          | ...          | >19.5       | 0.35        | J      |
| Teplitz99      | 180                        | 21.75           | ...          | ...          | ...         | ...         | J      |
| Saracco099     | 20                         | 23.75           | ...          | ...          | [18.0,24.0] | 0.36        | J      |
| Vaisinon00     | 2520,1275                  | 18.25,19.25     | [17.0,19.5]  | 0.40-0.45    | ...         | ...         | J      |
| Iovino05       | 180,270                    | 18.5,20.5       | [16.0,20.5]  | 0.54         | ...         | ...         | J      |
| Malhar01       | 4                          | 26.25           | ...          | ...          | [21.1,25.1] | 0.23        | J      |
| Saracco01      | 13.6                       | 24.25           | ...          | ...          | >20         | 0.34        | J      |
| Iovino05       | 391                        | 22.25           | [17.25,22.25] | 0.39±0.06   | ...         | ...         | J      |
| Feulner07      | 925                        | 22.25           | ...          | ...          | ...         | ...         | J      |
| Imai07         | 750,306                    | 19.625,20.375   | <18.00       | 0.39±0.02    | >19.5       | 0.30±0.03   | J      |
| This work      | 1588,392                   | 21.0,22.0       | [17.0,18.5]  | 0.44±0.04    | [19.5,22.0] | 0.34±0.01   | J      |

Notes.

a 3σ limit for point sources.
b 50% efficiency for point objects.
c The latest magnitude bin in the number counts.
Im−type galaxies at high-z three NIR filters. reproducing the feature of the slope turn down in the in Figures 23–26, fit the galaxy counts in the optical and NIR Early Sp code using was used for the two later-type galaxies. The reddening in the Table 4 are a Considering Notes. E/S0 Single star pop. τZ/Z Galaxies Type Functional Form z providing evidence that the elliptical population at the elliptical population parameterized using φ⋆ the bulk of the ellipticals as parameterizations is displayed in Figure 27, showing that at z ∼ 1 the implied number density of E/S0 galaxies is only ∼ 1/4 of the present day φ∗(0). Density evolution in the early-type galaxies was observed in previous works studying the type-dependent LF evolution (Kauffmann et al. 1996; Fried et al. 2001; Aguerri & Trujillo 2002; Wolf et al. 2003; Giallongo et al. 2005; Ilbert et al. 2006). Wolf et al. (2003) found an increase in φ of an order of magnitude for the early-type galaxies from z ∼ 1.2 to z = 0, that is over the φ∗ ∝ (1 + z)−2 simulated here. However, they used the spectra of a present-day Sa-type galaxy to separate different galaxies, which leads to an overestimation of number-density evolution for the early-type group. In Abraham et al. (2007), it is shown that the evolution in the fraction of the stellar mass locked in massive early-type galaxies is produced in the interval 0.7 < z < 1.7. A model in which φ for the elliptical galaxies is constant to z ∼ 0.6 and then evolve as φ∗ ∝ (0.4 + z)−2 for higher redshifts also produces a good fit to the optical and NIR counts (see Figures 23–26). In this model the population of red elliptical galaxies has doubled since z = 1, in good agreement with the increase of a factor of ∼ 2 in the number evolution of red galaxies given in Bell et al. (2004).

Finally, we have implemented a simple recipe to simulate downsizing in the elliptical population by maintaining φ constant with redshift for the LF of bright galaxies. The results are compatible with our NIR galaxy counts and B-band counts from the literature in the case that φ∗ is constant with redshift for red ellipticals brighter than M∗ – 0.7 (~ −22.0 in the Sloan r′ band in the AB system), decreasing the number densities for the bulk of the ellipticals as φ∗ ∝ (1 + z)−2.

6. COLOR ANALYSIS

More information about the evolution of the galaxy populations could be obtained from color histograms. The separate number counts in each band at the magnitude ranges that we sample are less sensitive to the formation redshift (for values zf >= 4) or the e-folding timescale of the star formation than

\[
\exp \left( -Q/\beta \left( 1 + z \right)^{-\beta} \right)
\]

given by Broadhurst et al. (1992) could be used with similar results. In this case, we used Q = 3 to parameterize the decrease in number of E/S0 galaxies, and Q = 1 to produce the required merger rate in the late spirals and irregulars. The number evolution given by these parameterizations is displayed in Figure 27, showing that at z ∼ 1 the implied number density of E/S0 galaxies is only ∼ 1/4 of the present day φ∗(0). Density evolution in the early-type galaxies was observed in previous works studying the type-dependent LF evolution (Kauffmann et al. 1996; Fried et al. 2001; Aguerri & Trujillo 2002; Wolf et al. 2003; Giallongo et al. 2005; Ilbert et al. 2006). Wolf et al. (2003) found an increase in φ of an order of magnitude for the early-type galaxies from z ∼ 1.2 to z = 0, that is over the φ∗ ∝ (1 + z)−2 simulated here. However, they used the spectra of a present-day Sa-type galaxy to separate different galaxies, which leads to an overestimation of number-density evolution for the early-type group. In Abraham et al. (2007), it is shown that the evolution in the fraction of the stellar mass locked in massive early-type galaxies is produced in the interval 0.7 < z < 1.7. A model in which φ for the elliptical galaxies is constant to z ∼ 0.6 and then evolve as φ∗ ∝ (0.4 + z)−2 for higher redshifts also produces a good fit to the optical and NIR counts (see Figures 23–26). In this model the population of red elliptical galaxies has doubled since z = 1, in good agreement with the increase of a factor of ∼ 2 in the number evolution of red galaxies given in Bell et al. (2004).

Finally, we have implemented a simple recipe to simulate downsizing in the elliptical population by maintaining φ constant with redshift for the LF of bright galaxies. The results are compatible with our NIR galaxy counts and B-band counts from the literature in the case that φ∗ is constant with redshift for red ellipticals brighter than M∗ – 0.7 (~ −22.0 in the Sloan r′ band in the AB system), decreasing the number densities for the bulk of the ellipticals as φ∗ ∝ (1 + z)−2.

6. COLOR ANALYSIS

More information about the evolution of the galaxy populations could be obtained from color histograms. The separate number counts in each band at the magnitude ranges that we sample are less sensitive to the formation redshift (for values zf >= 4) or the e-folding timescale of the star formation than

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6. COLOR ANALYSIS

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Figure 21. Galaxy number count in the $B$ band taken from the literature. The lines correspond to the number counts predictions from the models in Cristóbal-Hornillos et al. (2003) and Eliche-Moral et al. (2006). Also it is shown a model where only the passive evolution of stellar populations is considered (PLE).

(A color version of this figure is available in the online journal.)

Figure 22. Color evolution with redshift of the NIR colors for an elliptical and an early spiral (with the parameterizations given in Table 8). The two upper lines correspond to the $J - K_s$ color whereas the other two correspond to the $J - H$ color. The horizontal dotted lines correspond to the $J - H \sim 0.97$ and $J - K_s \sim 1.84$ colors of the fitted point for the slope change.

color histograms. Figure 28 shows the color–magnitude diagram built with the ALHAMBRA data through the filter centered at 6130 Å (F613) and $K_s$. The modeled evolutionary tracks for the four galaxy spectra considered in Table 8 are also displayed. Models with no evolution (top panel) and passive evolution (bottom panel ) have been considered. As can be appreciated, the evolved spectra produce better match to the data than the no-evolved version, principally at the faint blue end which is better described by models considering passive evolution in the late Sp and Irr spectra.

Figure 29 shows the color–$K_s$ color histogram for different $K_s$ magnitude bins. We have used an e-folding timescale $\tau = 0.7$ Gyr to describe the elliptical galaxies in those plots; this longer timescale produces better fits to the red end of the color histograms than an instantaneous star-forming event which overpredict the number of red galaxies. Both models produce similar results when fitting the galaxy counts in individual optical and NIR bands. The simulated histograms correspond to models where the population of E/S0 galaxies decrease with redshift, the population of spirals stay constant, and the late-type galaxies increase as $\phi^* \propto (1 + z)^2$ conserving the luminosity densities. The population of early spiral galaxies have been divided in two classes: one remain as in Table 8, whereas the amount of extinction has been doubled for the other. This tries to avoid the fact that the discretization of the actual galaxy population in four classes tend to produce sharp histograms.

As can be appreciated, the models reproduce the overall shape of the data for bright $K_s$ magnitudes. Nevertheless, at faint $K_s$ magnitudes the models predict higher values in the color range $3 \lesssim F613-K_s \lesssim 5$. As could be inferred from Figure 29 to obtain a better match to the data the number densities of early spiral galaxies formed in a shorter timescale has to decrease with $z$, such fading of the spirals will lead to an underprediction of the blue-band number counts unless that the number of star-forming increases at higher redshift. In Figure 30, the F613-$K_s$ histograms for the $K_s$ bins: $[16.5, 17.5], [17.5, 18.5]$ show a better concordance with the observed data. Those histograms correspond to a model where the number densities for the early spirals decrease with $z$ as $\phi^* \propto (1 + z)^{-1}$, the late-type spiral number density remain constant with redshift, and the number densities of Irr galaxies increase $\propto (1 + z)^3$. The luminosity density is not conserved within any galaxy class. Similar results could be obtained using $\phi^* \propto \exp\left(-(Q/\beta)(1+z)^{-\beta} - 1\right)$ (Broadhurst et al. 1992), with $Q = -1$, and $Q = 3$ to describe the number evolution of early spiral and Irr galaxies. This number evolution formulation avoids a step increase of Irr galaxies at high redshift. However in Figure 30 a shortage of red galaxies is seen at about $F613-K_s \sim 5$, which could be due to the fact that we only use a discrete number of galaxy parameterizations, for example, the existence of dusty starburst with the same red colors than the passive extremely red objects (Daddi et al. 2000) is well known. Covering a wider range
in galaxy internal extinction or formation timescale will tend to smear the bi-modality present in the simulated histograms. As could be seen in Figure 31, the number counts produced by this model in *B* + NIR filters also produce good fits to the observed data points. In these models, the number counts at faint magnitudes will be dominated by the star-forming galaxies. The number count slope at faint magnitudes will be $-0.4(\alpha + 1)$ (Bershady 2003), with $\alpha$ being the slope of the dominant luminosity function for $M \ll M^\ast$. With this parameterization, the slope of the number counts tends to 0.36 at the fainter end.

7. SUMMARY

We have presented galaxy counts in the *J*, *H*, and *Ks* filters covering an area of 0.45 deg$^2$ and an average 50% detection efficiency depth of $J \sim 22.4$, $H \sim 21.3$, and $Ks \sim 20.0$ (Vega system). The depth reached, and the precision of the counts over a range of 5 mag makes the data valuable for examining the change of the count slope reported in the *Ks* filter, and to extend this examination to the *J* and *H* bands. We find that a change in slope occurs in each of the NIR bands in the range $J = [18.5, 19.5]$, $H = [18.0, 19.0]$, and $Ks = [17.0, 18.0]$. The NIR colors where the break in the galaxy counts are found imply that this change is related to the population of red galaxies at $z \sim 1$.

We have compared our number counts results with predictions from a wide range of number-count models, concluding that in order to reproduce the described changes in the NIR slopes, a decrease in bulk of the population of red-elliptical galaxies is needed. Good fits to the *B*-band and NIR counts are obtained with a parameterization for the number evolution of the elliptical population as $\phi^\ast \propto (1 + z)^{-2}$ with no accompanying evolution.
in $M^*$, corresponding to evolution in which the majority of ellipticals formed in spiral–spiral mergers.

Performing a color analysis shows that also the population of early spirals has to decrease at higher redshift in order to describe the color distribution in $r-Ks$. Models using the parameterization of Broadhurst et al. (1992) $\phi^* \propto \exp \left(-Q/\beta((1+z)^{-\beta} - 1)\right)$, with $Q = -3$, $Q = -1$, and $Q = 3$ to describe the number evolution of ellipticals, early spiral and Irr galaxies, with no number density evolution for late-spiral systems, produce good fits to the observed distribution, avoiding at the same time a high number of young systems at high $z$. A good match to the optical and NIR data is also obtained if the population of red galaxies in the models remain constant to $z \sim 0.6$ and afterwards its number density decreases as $\phi^* \propto (0.4 + z)^{-2}$, or if the number density of red-ellipticals is constant with redshift for galaxies brighter than $M^* - 0.7 \sim -22.0$ in the Sloan $r'$ band in the AB system), decreasing as $\phi^* \propto (1 + z)^{-2}$ for the bulk of the ellipticals.

Alhambra is processing the data obtained in 20 medium-band optical and three NIR filters reaching high-quality photometric redshift measurements ($\Delta z/(1 + z) \leq 0.03$). Also an accurate classification by SED will be acquired. Those data will allow for the study of the evolution of the different galaxy types to $z \sim 1$, which will complement the results given in this article, disentangling what populations contribute to the number counts at different redshift intervals. Also the study of number counts for red galaxy populations, passive EROS or BzK (Daddi et al. 2004) galaxies will constrain the formation redshift and formation timescale for massive elliptical galaxies.

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Figure 27. Functional form of the $\phi^*$ evolution parameterization.

Figure 28. Color–magnitude diagram for the Alhambra data in the filter with effective wavelength 6130 Å (F613) and $K_s$. The tracks for the galaxy classes in Table 8 formed at $z_f = 4$ are also shown, for the passive evolution scenario top panel, and the no-evolution case bottom panel. Each galaxy track is computed for the characteristic luminosity given in Table 9. The solid tracks from top to bottom correspond to a simulated E/S0 galaxy with single stellar population and e-folding timescales $\tau = 0.5$, 1 Gyr. The dashed lines correspond to the early- and late-type spiral galaxies, and the dotted line to the Irr galaxy. The vertical dotted line and the diagonal one are the 5$\sigma$ detection levels. The two dashed lines join the spectra points for $z = 0.5$ and $z = 1.0$. The median color for each $K_s$ bin is marked with crosses.

Figure 29. Color F613-$K_s$ histogram (normalized for 1 deg$^2$) for sources in different $K_s$ bins. The histograms produced by the models have been convolved with a Gaussian kernel $\sigma = 0.2$ in order to reproduce the photometric errors. The histograms computed for each population are shown in red for the E/S0, green for the early-type spiral galaxies, and in blue for the late-type spirals and Irr galaxies.

(A color version of this figure is available in the online journal.)
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APPENDIX

INDIVIDUAL IMAGE COMBINATION

As mentioned in the text, to combine the processed images we used SWARP (Bertin et al. 2002). With this software, individual images were projected into subsections of the final frame using the inverse mapping, in which each output pixel center was associated with a position in the input image at which it is interpolated. With this schema, the code corrected at the same time the geometrical distortions in the individual images using the astrometric information stored in the image headers.

A.1. Estimating the Relative Transparency

Using a filtered version of the SExtractor catalogs computed over the sky-subtracted images, an accurate estimate of the relative transparency was computed by tracing the high-S/N objects in all the images. The relative transparency values were used inside SWARP to scale the individual images to the same flux level in order to uniformize the zero points in the outer dither areas, this allowed to use 2MASS catalogs to calibrate the ALHAMBRA NIR photometry in the final images.

A.2. Astrometry Calibration

When computing the resampled version of the individual frames, SWARP uses the WCS information stored in the headers. In order to obtain a better matching of the individual images, first the pipeline calculated the external astrometrical solution for a reference image. The individual images were then calibrated internally with respect to it, thus obtaining the equatorial coordinates from the reference image. In this paper, the individual image with better transparency in a given pointing was used as reference. However, to get a better internal astrometry between the different filters, after completing a pointing in the 23 ALHAMBRA filters, the images with better FWHM and transparency in a set of selected optical filters, are combined to produce a deep image that will be used afterward as reference.

We have determined that the USNO-B1.0 catalog (Monet et al. 2003) provides an adequate number of objects to perform a high-quality external astrometric calibration. We used our own code to match the sources with brighter apparent magnitudes in the reference image with those in the USNO-B1.0. Once a meaningful number of pairs were identified, the CCMAP IRAF task was used in two iterations to acquire the required astrometric solution with a second-order polynomial. A histogram of the external astrometric solution rms and the number of objects used for the final images of ALH08 is shown in Figure 32. The median external astrometry rms is 0.′12 in RA and 0.′11 DEC.

Having calibrated a reference image, the rest of the individual images were calibrated internally. The median internal rms in the astrometric solution for the OMEGA2000 data used in this paper is 0.′06 in R.A. and decl. using a median of 160 objects, as shown in Figure 32.

Figure 30. Color F613-Ks histogram for sources in different Ks bins. The histograms have been normalized to 1 deg$^2$. The modeled histograms have been computed for models in which the number densities for the early spirals decrease with redshift as $\phi_e \propto (1 + z)^{-2}$, the late-type spirals number density remain constant with redshift, and number densities of Irr galaxies increase proportional to $(1 + z)^3$. The number of E/S0 galaxies decrease with $z$ as specified in the labels. The histograms obtained with this models have been convolved with a Gaussian kernel $\sigma = 0.2$ in order to reproduce the photometric errors.

\[ \phi_e \propto (1 + z)^{-2} \]

\[ \phi_e \propto (0.4 + z)^{-2}; z > 0.6 \]

\[ \phi_e \propto (1 + z)^{-2}; M > M^* - 0.7 \]

\[ \phi_e \propto \exp(-0.6(1 + z)^4 - 1) \]
Figure 31. Differential number counts in the B and NIR bands compared with a models in which the number densities for the early spirals decrease with redshift as \( \phi^* \propto (1 + z)^{-1} \), the late-type spirals number density remain constant with redshift, and number densities of Irr galaxies increase \( \propto (1 + z)^3 \).

Figure 32. Histograms of the astrometry solution rms for the ALH08 images. Top panel: external USNO-B1.0. Bottom panel: internal. The small panels show the histograms of the number of objects that enter into the final astrometry fitting.

Table 10

| Combining with median | Nearest | Bilinear | Lanczos2 | Lanczos3 | Lanczos4 |
|-----------------------|---------|----------|----------|----------|----------|
| 1 pixels              | +0.017  | +0.186   | +0.112   | +0.074   | +0.068   |
| 2 pixels              | −0.035  | −0.013   | −0.072   | −0.059   | −0.101   |

Combining with average

| 1 pixels              | +0.035  | +0.274   | +0.177   | +0.156   | +0.130   |
| 2 pixels              | −0.030  | −0.018   | −0.069   | −0.110   | −0.083   |

A.3. Image Co-Adding

Swarp allows the user to choose among several interpolation functions for inverse mapping. For selecting the more appropriate kernel, we analyzed the resulting final image FWHM and its pixel-to-pixel correlation. Table 10 shows the correlation values, between adjacent pixels and for pixel pairs separated by 2 pixels, in the final images obtained using different available interpolation functions. As can be seen in the table, the bilinear function produces a higher correlation which translate into an underestimation of the flux errors. Using the Lanczos-3 function, the FWHM of the final image was improved by \( \sim 0.05 \) compared with the nearest-neighbor interpolation, whereas the autocorrelation at 1 pixel remain acceptable \( \sim 0.16 \) (when the images are combined using the average). The Lanczos-4
function did not decrease substantially, neither the correlation at 1 pixel nor the FWHM; in contrast it produced large artifacts at the bad pixels and image borders, so finally we have decided to take the Lanczos-3 function.

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