Evolution of faint galaxy clustering:

The 2-point angular correlation function of 20,000 galaxies to \( V < 23.5 \) and \( I < 22.5 \).*

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Abstract. The UHSK wide field camera of the CFHT was used to image 0.68 deg\(^2\) of sky. From these images, \( \sim 20,000 \) galaxies were detected to completeness magnitudes \( V < 23.5 \) and \( I < 22.5 \). The angular correlation function of these galaxies is well represented by the parameterization \( \omega(\theta) = A_W \theta^{-\delta} \). The slope \( \delta \simeq -0.8 \) shows no significant variation over the range of magnitude. The amplitude \( A_W \) decreases with increasing magnitude in a way that is most compatible with a \( \Lambda \)CDM model (\( \Omega_0 = 0.2, \Lambda = 0.8 \)) with a hierarchical clustering evolution parameter \( \epsilon > 0 \). We infer a best-fit spatial correlation length of \( r_0 \simeq 5.85 \pm 0.5 \) h\(^{-1}\) Mpc at \( z = 0 \).

The peak redshift of the survey (\( I \leq 22.5 \)) is estimated to be \( z_{\text{peak}} \simeq 0.58 \), using the blue-evolving luminosity function from the CFRS and the flat \( \Lambda \) cosmology, and \( r_0(z_{\text{peak}}) \simeq 3.5 \pm 0.5 \) h\(^{-1}\) Mpc. We also detect a significant difference in clustering amplitude for the red and blue galaxies, quantitatively measured by correlation lengths of \( r_00 = 5.3 \pm 0.5 \) h\(^{-1}\) Mpc and \( r_{00} = 1.9 \pm 0.9 \) h\(^{-1}\) Mpc respectively, at \( z = 0 \).

Key words: galaxies - angular correlation function - clustering - survey

1. Introduction

For the past decade, the study of the spatial Large-Scale Structure (LSS) of the universe has become an major tool for constraining the cosmological models. In particular, provided many assumptions on how morphological type correlates with colour, how mass is correlated with optical luminosity, and how local density correlates with morphology, recent CDM hierarchical N-body simulations and semi-analytic models of galaxy formation are able to make tentative predictions on the clustering evolution of the galaxies as a function of their redshifts, spectral types and star formation rates (Kauffmann et al., 1999a; 1999b). By measuring redshifts for \( 10^9 \) or more galaxies, the next generation redshift surveys such as the VIRMOS survey (Lefèvre et al., 1998), the DEEP survey (Davis and Faber, 1998), and the LZT survey (Hickson et al., 1998; see also http://www.astro.ubc.ca/LMT/lzt/index.html) will allow detailed studies of the large-scale clustering and its evolution to \( z \sim 1 \).

Until these surveys are completed, the measurement of the 2-point angular correlation functions \( \omega(\theta) \) of large photometric galaxy samples remains the best alternative to constrain galaxy clustering at \( z > 1 \). The major caveat of \( \omega(\theta) \), as opposed to the 2-point spatial correlation function \( \xi(r) \), is that it probes the projection of a 3D distribution of the galaxies onto the 2D celestial sphere. i.e. one can not tell whether a given galaxy is a faint nearby object or a bright remote one. As a consequence, \( \omega(\theta) \) is sensitive to the effects of both the intrinsic 3D clustering and the luminosity evolution (LE) of galaxies for a given set of cosmological parameters. To avoid this degeneracy, one must choose between two approaches to extract sensible information from \( \omega(\theta) \). First, one may use past observations to assume a scenario of galaxy evolution with given LEs and redshift distributions for each galaxy population, and then deduce the clustering evolution. A second approach would be to assume a clustering scenario, cosmological parameters, and to measure the evolution of the correlation function in order to validate the theoretical LE used to model the galaxy counts, e.g. Roche et al. (1993c). In this paper, we favour the first approach. We use the Canada-France Redshift Survey (CFRS; Lilly et al. 1996) luminosity function and redshift distribution to invert the angular correlation function with Limber’s formula (cf section 3 on modeling of \( \omega(\theta), \xi(r) \) and \( r_0 \) ) to compute the spatial correlation length from the amplitude of \( \omega(\theta) \). This approach has several limits which are discussed in section 3.

An extensive literature covers the evolution of clustering using \( \omega(\theta) \). The first attempts to describe clustering using counts in cells is due to Limber (1954). The two-
point correlation function as a statistical diagnosis of clustering has been popularized in astrophysics by Hauser & Peebles (1974) and applied to the Zwicky Catalog (Peebles and Hauser, 1974). Since these pioneering studies, the method, fully described by Peebles (1980), has been applied to many photographic catalogues in diverse photometric bands e.g. see Groth & Peebles (1977), Koo & Szalay (1984), Maddox et al. (1990) where the clustering is studied on large angular scales. Using Limber’s (1953) formula relating $\omega(\theta)$ to the spatial correlation function $\xi(r)$, these studies establish that the spatial clustering of local galaxies is studied on large angular scales. By parameterizing as a power law, $\xi(r) = (r/r_0)^{-\gamma}$, where the correlation length $r_0 \approx 4 - 8 h^{-1} \text{Mpc}$ ($h = H_0/100$) and the slope $\gamma \approx 1.7 - 1.8$.

A second generation of studies based on small-scale CCDs, probes smaller areas to deeper magnitudes (Estathiou et al., 1991; Campos et al., 1993; Neuschaefer et al., 1994; Neuschaefer et al., 1994; Roukema and Peterson, 1994; Brainerd et al., 1995; Brainerd and Smail, 1998; Brainerd et al., 1999; Hudon and Lilly, 1990; Lidman and Peterson, 1994; Roche et al., 1993; Roche et al., 1996; Voids and Fahnlin, 1997), therefore allowing to measure the evolution of the correlation length to redshifts $z \lesssim 1$. The most recent studies take advantage of large area CCD detectors (Roche and Eales, 1999; Postman et al., 1998) to measure the angular correlation function, and of the use of photometric redshifts (Koo, 1999) to estimate the spatial correlation function from deep photometric surveys (Illumsen et al., 1997; Arnouts et al., 1999). Despite these numerous studies, our knowledge of the clustering of galaxies is still rudimentary. The main trends are that while a mild luminosity evolution seems to be required to explain faint number counts in the $I$-band, weak or no evolution in the galaxy clustering with redshift is detected out to $z \sim 1$.

The existing surveys measuring the galaxy angular correlation function, and covering a broad range of magnitude bands and limits, constrain the value of $r_0(z_{\text{peak}})$ to the range $1.5 - 4.5 h^{-1}\text{Mpc}$ for $0.5 \leq z_{\text{peak}} < 1$. This dispersion is mainly due to the uncertainty in our knowledge of the luminosity functions and redshift distributions for the different galaxy types at $z \sim 1$ (section 6), and possibly to the varying selection biases from survey to survey. To be consistent with the values of $r_0(z_{\text{peak}})$ measured from the nearby redshift surveys and ranging from $4h^{-1}\text{Mpc}$ to $8h^{-1}\text{Mpc}$ (de Lapparent et al., 1988; Loveday et al., 1992; Cole et al., 1994; Tucker et al., 1997; Ratcliffe et al., 1998; Rizzo et al., 1998), most observations of the galaxy clustering favour either constant or increasing clustering with time in proper coordinates, which is consistent with N-body simulations of CDM hierarchical universes (Davis et al., 1985; Baugh et al., 1999; Hudon and Lilly, 1994).

Note that only a few redshift surveys allow a direct study of the evolution of the spatial clustering (Lilly et al., 1992; Connolly et al., 1998; Arnouts et al., 1999; Carlberg et al., 2000): these surveys measure $r_0(z_{\text{peak}}) \approx 1.4 - 4.5 h^{-1}\text{Mpc}$ for $0.5 \leq z_{\text{peak}} < 1$. We underline that except for the results of Carlberg et al. (2000), corresponding to the high value of $r_0(z_{\text{peak}})$, the limited area of the mentioned surveys make them very sensitive to cosmic variance, and the corresponding results on the correlation function must be taken with caution.

Moreover, the existing analyses have not yet answered convincingly to the following two questions: Is there an evolution of the angular correlation function slope $\delta = \gamma - 1$ at faint limiting magnitudes? And do red-selected objects and blue-selected objects show a true difference in 3-D clustering? In addition to providing another measure of the galaxy clustering at $z \sim 0.5$, the new sample presented here allows us to address these questions. The paper is organized as follows, the observations are described in section 2, section 3 presents the data reduction, section 4 addresses the star/galaxy separations and counts. Section 5 details the analysis of the correlation function, section 6 gives the results, and section 7 provides a discussion of our results and a comparison with previous work.

### 2. Observations

The data were obtained during the spring of 1998 using the prime-focus wide-field UH8K CCD Camera (Metzger et al., 1997) at the Canada-France-Hawaii 3.6 m Telescope. The camera is a mosaic of $8 \times 4k$ CCD chips covering a total area of $\sim 28' \times 28'$ with a scale of $0.206''$/pixel. We observed four fields with R.A. offset of 23', 23', and 17', hence overlapping by 5', 5' and 10' (Table I). The observations were done in bands $V$ (Johnson) and $I$ (Cousins). The total area of the survey is $0.68 \text{deg}^2$. The limiting magnitudes are $V < 24$ and $I < 23$ (see section 3.3 on the completeness). The central galactic coordinates are $l = 126.2^\circ$, $b = 68.2^\circ$. At such high galactic latitudes, the reddening is $E(B-V) < 0.03 \text{mag}$ (Burstein and Heiles, 1982). This is an upper limit because we observed in $V$ and $I$ (reddening $\sim \lambda^{-1}$). We neglected both the absolute reddening and the relative reddening between the fields. Table I gives the characteristics of each field. The seeing is between $0.7''$ and $0.8''$ for both filters during the whole night. The exposure time is $1200 \text{sec}$ for all fields. Figure I shows the map of the $\sim 19,500$ galaxies detected to $I < 22.5$ (limiting magnitude of the correlation analysis, cf section 3.3). In spite of the bad cosmetics of CCD#4 (visible in the upper right corner of Fig. I), the 5' overlaps provide homogeneous sampling of the area, except for the regions containing bright stars (empty circle in the upper middle) and the gaps within the UH8K Mosaic CCD chips.

### 3. Data reduction

The data were reduced using FLIPS by J.C. Cuillandre as part of the calibration service of the 1998 season of UH8K.
**Fig. 1.** Map of 19,506 galaxies to $I < 22.5$. Bad cosmetics, intervals between CCD chips, and saturation artifacts due to bright stars are masked (shown as empty areas).

**Table 1.** Field characteristics

| Field | $\alpha_{2000}$ hr min sec | $\delta_{2000}$ ° ′ ′′ | airmass in V | airmass in I |
|-------|-------------------------|---------------------|-------------|-------------|
| UD02  | 12 37 55.3             | +49 08 50.6         | 1.491       | 1.161       |
| UD03  | 12 40 15.6             | +49 08 52.3         | 1.371       | 1.148       |
| UD04  | 12 42 35.8             | +49 08 54.1         | 1.285       | 1.154       |
| UD05  | 12 44 06.3             | +49 08 55.3         | 1.224       | 1.176       |

Camera, Cuillandre (1998a; 1998b). FLIPS suppresses the dark and bias using the CCD overs-cans and flattens the response of the 8 detectors using a flat-field made by combining $\sim 300$ images of 18 nights of observation with the UH8K Camera. The final images have a corrected sky flux showing variations of less than 1% within each CCD image. The photometric standards were pre-reduced following exactly the same steps. The final dataset consists of 64 $2k \times 4k$ frames (32 in V, 32 in I), and a set of photometric standard stars.

Photometry was performed using the SExtractor Package (Bertin and Arnouts, 1996) which provides Kron-like elliptical aperture and isophotal fluxes, $(X, Y)$ coordinates, position, elongation and stellarity class for all objects above a given threshold (we choose a threshold of 25 contiguous pixels above $1.5\sigma$ of sky value in V and I). The resulting SExtractor files were then calibrated for astrometry and photometry.

**3.1. astrometry**

The USNO-A2.0 Astrometric Catalogue (Monet, 1998) is used as the astrometric reference as it gives the equatorial coordinates of most objects in our fields to a red mag $\leq 20$ with accuracies of $\leq 0.5''$, and because it is easily accessible via on-line astronomical databases. The astrometry is done separately on the 64 frames, with IRAF geomap/geotran second-order Legendre polynomials. A radial correction is applied previously on the $(X, Y)$ coordinates to correct the prime-focus optical corrector distortion, whose equations were provided by J.C. Cuillandre (1996). If $R$ is the actual radial coordinate of an object from the center of the UH8K mosaic (in mm) and $r$ its observed radial coordinate (in mm), then the shift $r - R$ due to the corrector is

$$r - R = 9.07 \times 10^{-7} r^3 + 2.06 \times 10^{-12} r^5$$

$$r = 0.07284 \theta (1 + 2.593 \times 10^{-9} \theta^{2.093}).$$  \hspace{1cm} (1)

$\theta$ is the angular distance of the object from the center in arcsec. According to eq. (1), the radial distortion is 0.13 pixel at a radius of 3′, 0.32 pixel at 4′, and it becomes non-negligible for radii greater than 6′ where the distortion is greater than one pixel (e.g. the radial distortion at 14′ is 14.1 pixels). The overlaps between the fields allow us to verify the importance of the optical distortion correction on the accuracy of the final astrometry. Figures 2 and 3 show the errors $\Delta \alpha$ and $\Delta \delta$ in X and Y directions for the overlap between the fields UD03 (CCD #0) and UD04 (CCD #6) without correction of distortion (Fig. 2) and with correction (Fig. 3). One can see that both the systematic errors and the random errors are below 0.5″ after correction. We are not able to remove completely the systematic shifts between the fields (Fig. 3 frame a and b). This may be due to unknown misalignments between the chips of the mosaic. One can only minimize the system-
Fig. 2. Differences between the equatorial coordinates of the objects of the overlapping region of the fields UD03-CCD#0 and UD04-CCD#6 (in arcsec) if no correction is applied for the prime focus optical corrector distortion. (a) shows the right ascension difference $\Delta \alpha$ vs the CCD X axis, (b) shows $\Delta \alpha$ vs the CCD Y axis, (c) shows the declination difference $\Delta \delta$ vs the CCD X axis, and (d) shows $\Delta \delta$ vs the CCD Y axis. Important systematic effects are seen in frame (c) and (d).

Fig. 3. Same as Fig. 2 with the correction of the prime focus optical corrector distortion of eq. (1).

### 3.2. photometry

A rigorous photometric calibration is usually performed by applying a linear transformation on the instrumental (observed) magnitude $m$ of the objects (given by Sextractor Kron-like elliptical aperture fluxes),

$$ M = m - A_m \times \chi + k_m \times \Delta m + m_0, $$

(2)

where $M$ is the standard magnitude, $A_m$ is the extinction coefficient, $\chi$ is the airmass, $k_m$ is the true-colour coefficient, $\Delta m$ is the true colour and $m_0$ is the zero-point.

In principle, the coefficient $A_m$ must be derived from the observation of a field of standard stars at three different airmasses, and the coefficients $k_m$, from a large range of star colours. Because the zero-points $m_0$ and the colour coefficients may vary from CCD chip to CCD chip, one should also observe the standard field separately in the 8 CCDs of the mosaic at least three times through the night.

For the UH8K Camera, this task is clearly beyond the observer’s reach because the reading time of the UH8K camera is too long and the whole night would not be sufficient to observe the fields required for a proper photometric calibration. In fact, the dataset provided by the service observing consists of one field of standard stars SA104 (Landolt, 1992), observed in the middle of the night, in $I$ and $V$. This minimal observation only allows one to measure an average zero-point over the whole mosaic in each.
filter by combining all the standard stars (one or two per CCD chips).

We derive the colour coefficients $k_V$ and $k_I$ and the magnitude zero-points $V_0$ and $I_0$ by least-square fit of the colour transformation equations to the SA104 sequence:

$$(V - m_V) = k_V \times (V - I) + V_0 \quad (3)$$

$$(I - m_I) = k_I \times (V - I) + I_0 \quad (4)$$

The airmass correction is included in the $m_V, m_I$ magnitudes, and we use the standard CFHT values for a thick CCD, $A_V = -0.12$ and $A_I = -0.05$ (http://www.cfht.hawaii.edu/Instruments/Imaging/FOCAM/appen.html#F) The results appear in Table 2. For comparison, the Table also lists another US8K measurement obtained by J.C. Cuillandre as part of the calibration service of the US8K 1996 season; no corresponding errors are noted.

For further control, we also derive the $k_V$ and $k_I$ coefficients from a synthetic standard sequence: synthetic “instrumental” magnitudes are computed for a set of stellar template spectra of different colours by a routine which uses the theoretical transmission curve of the instrument optics + filter (Arnouts, priv. comm. 1999). Application of eq. (3) and (4) to the synthetic sequence yields the “synthetic” $k_V$ and $k_I$, also listed in Table 2. The corresponding zero-points $V_0$ and $I_0$ are derived in a second step by application of eq. (3) and (4) to all stars of the SA104 sequence, this time with the “synthetic” $k_V$ and $k_I$.

The colour coefficient $k_V$ derived from the synthetic sequence is compatible with the other values listed in Table 2. A significant dispersion appears in the $k_I$ measurements, probably because this coefficient is small. The zero-points $V_0$ and $I_0$ listed in Table 2 are also consistent within the error bars and are poorly dependent on the colour coefficients. Because the colour coefficients $k_V$ and $k_I$ derived from SA104 display large errors, we choose to adopt the colour coefficients from the synthetic sequence and the corresponding zero-points calibrated on SA104: $k_V = -0.035 \pm 0.001$ and $k_I = 0.005 \pm 0.0003$; $V_0 = 24.58 \pm 0.018$ and $I_0 = 24.76 \pm 0.014$.

For all observed objects in the catalogue, the instrumental magnitudes are converted into standard $V$ and $I$ magnitudes by re-writing the colour equations eq. (3) and (4), written in terms of the standard colour $V-I$, into functions of the measured instrumental colours ($m_V - m_I$):

$$V = m_V - A_V \times \chi + \frac{k_V \times (m_V - m_I)}{1 + k_I - k_V} + V_0 \quad (5)$$

$$I = m_I - A_I \times \chi + \frac{k_I \times (m_V - m_I)}{1 + k_I - k_V} + I_0 \quad (6)$$

$m_I, m_V$ are the observed magnitudes (Kron elliptical apertures), and $k_V, k_I, V_0$ and $I_0$ are the values labeled “synthetic” in Table 2. The other coefficients have the same meaning as those of eq. (2), and we use, as in eq. (3) and (4), the standard CFH values $A_V = -0.12$ and $A_I = -0.05$.

The astronomer in charge of the service observing stated that the night was clear with only thin cirrus visible near the horizon at sunrise (Picat, priv. comm. 1998). The overlapping regions between the various mosaic fields observed can be used to estimate the possible variations in the zero-points during the night. The fields were observed in the following sequence: UD02-I, UD03-I, UD04-I, UD05-I, UD05-V, UD04-V, UD03-V, UD02-V. Figure 5 plots the average of the magnitude differences $\Delta$mag for the bright objects (with $I < 19$ and $V < 20$) detected in the overlapping CCD regions as a function of sidereal time. For each mosaic field observed, there are 2 to 4 CCD’s presenting an overlap with a CCD within another field, and each average $\Delta$mag is plotted at the sidereal time of the first observed overlap.

A small systematic variation of the average $\Delta$mag, denoted $< \Delta$mag$>$, with sidereal time is detected in the $I$ filter, and possibly in the $V$ filter. A field-to-field correction of the zero-points is done to account for these small variations during the night: we apply to each field a correction in its zero-point measured by the $< \Delta$mag$>$ in Fig. 4, taking the fields UD02-I and UD02-V as references, and following the sidereal sequence; the same zero-point correction is applied for all the CCD of each mosaic field. The residual magnitude variations measured after correction in the CCD overlaps are $\sigma \approx 0.05$ mag in both the $V$ and $I$ filters. These put an upper limit on the variations in the zero-points and colour coefficients between the different CCD’s of the mosaic which are not accounted for in the present analysis. Note that a gradient remains in the $V$ data (see section 6.3), which will be removed using the variation of the average galaxy number counts variations with right ascension.

To evaluate the final photometric errors in the obtained catalogue, the $V$ and $I$ magnitudes of objects in the overlapping sections are also compared individually. Figure 6 gives the residuals in the $V$ and $I$ bands versus magnitude for all objects having $V-I$ colours (cf section 3.3) and Table 3 gives the corresponding standard deviations. The $V-I$ errors are taken to be $\sim \sqrt{2} \sigma_{\Delta V}$. The large dispersion at bright magnitudes in Fig. 6 is due to saturation effects. The “tilted” variation of the residuals with magnitude for residuals larger than 0.5 mag in absolute values (in both the $V$ and $I$ bands) is caused by the following effect: each object in the overlaps is given the magnitude measured in one of the overlap, arbitrarily. If the average of the 2 magnitudes in the overlap were used, this “tilt” would vanish. However, this affects only $\sim 0.5\%$ of the objects, and we consider that it would make no significant difference in any of the results reported here.
Table 2. Colour coefficients \( k \) for the \( V \) and \( I \) bands derived from the standard field SA104, J.C. Cuillandre’s calibration service, and S. Arnouts’ routine (labeled Synthetic, cf text). The average zero-points <zero-point> were derived using the associated \( k \).

| Source Filter     | \( k \)       | <zero-point> |
|-------------------|---------------|-------------|
| SA104 \( V \)     | 0.0 ± 0.05    | 24.62 ± 0.06|
| SA104 \( I \)     | 0.041 ± 0.041 | 24.72 ± 0.05|
| Cuillandre \( V \) | -0.033        | 24.629      |
| Cuillandre \( I \) | -0.066        | 24.721      |
| Synthetic \( V \) | -0.035 ± 0.001| 24.58 ± 0.018|
| Synthetic \( I \) | 0.005 ± 0.0003| 24.76 ± 0.014|

Fig. 4. Average magnitude differences \( \Delta \text{mag} \) of the bright objects present in the overlapping regions versus the sidereal time. The \( I \)-band data are shown as filled symbols, and the \( V \)-band data as open symbols. Time variations are always smaller than chip-to-chip zero-point errors.

Fig. 5. Photometric residuals \( \Delta V \) and \( \Delta I \) in the overlapping frames versus magnitude \( V \) and \( I \). The vertical lines indicate the completeness limits. The associated standard deviations are given in Table 3.

3.3. Magnitude and colour completeness

Three catalogues are generated from the data: one catalogue in the \( V \) band, one in the \( I \) band, and one catalogue containing objects with measured \( V - I \) obtained by merging the two catalogues. All objects whose centroids are separated by less than 1\( '' \) were merged, and their \( V - I \) are computed.

The completeness magnitudes of the \( V \) and \( I \) catalogues are defined to be one half magnitude brighter than the peak of the distributions. This corresponds to \( V_{\text{complete}} \simeq 23.75 \) and \( I_{\text{complete}} \simeq 22.75 \). Because some chips go deeper than others and because the correlation analysis is sensitive to chip-to-chip number density variations, we lower the completeness limit to the least sensitive chip (0.2 magnitude brighter), to which we add the chip-to-chip dispersion of \( 0.05 \) mag measured from Fig. 4. Hence, the final completeness limits are \( V_{\text{complete}} \simeq 23.5 \) and \( I_{\text{complete}} \simeq 22.5 \).

The colour completenesses in the \( V \) and \( I \) bands are given relative to one another in Fig. 3. The red galaxy completeness limit is determined primarily by how deep the \( V \)-band data extend. Because the \( V \)-band catalogue is only complete to \( V \simeq 23.5 \), faint objects redder than \( V - I > 1 \) will be missed near the limit of the \( I \) catalogue. (see Fig. 3 and 4 in section 4.3). This is an important fact to be remembered when making colour-selected correlation analyses.

4. Stars and galaxies

4.1. Star/galaxy separation

SExtractor computes a stellarity index for each detected object (in the interval 0-1, with 1 for stars, and 0 for galaxies). The stellarity index is determined from a non-linear set of equations (Trained Neural Network) \( \theta \) \cite{Bertin&Arnouts, 1996}. The good seeing of the images (0.7''–0.8'') allows a robust classification to \( V < 22 \) and \( I < 21 \). According to Bertin & Arnouts, the algorithm success rate...
at these magnitudes is 95% using data with a similar sampling and a seeing \( \sim 1'' \). Figure 6 shows the index of the \( \sim 30,000 \) objects detected both in \( V \) and \( I \). For \( I < 21 \) or \( V < 22 \), all objects with an index < 0.9 are classified as galaxies. This criterion classifies as galaxies only the objects showing a clear evidence of extendedness. For \( I > 21 \) or \( V > 22 \) objects with an index < 0.95 are classified as galaxies. Because at these faint magnitudes most objects have an index < 0.95 (the great majority of objects with a stellarity index higher than 0.95 are spurious detections), the threshold of 0.95 does not remove the remaining stars from the sample. To correct for the fact that most of the stars with \( V > 22 \) have been misclassified as galaxies, we need to apply a correction for the star dilution (see subsection on data-induced errors in section 5). We evaluated the stellar contamination with the Galaxy star-count model of Bahcall & Soneira (1988), which is compared on Figure 7 to the number counts of galaxies. The galaxies outnumber the stars by nearly an order of magnitude where the classification algorithm efficiency is less than 95% (vertical dotted line in the lower part of the diagrams).

4.2. Galaxy counts

The galaxy counts shown in Fig. 8 are in good agreement with other measurements. In the \( I \) band, we systematically measure \( 20 - 30\% \) more galaxies than Postman et al. (1998) up to \( I < 22 \). At \( I = 21.25 \), we count 5626 galaxies per \( \text{deg}^2 \), and Postman et al. find 4057. Given the errors in the \( I \) zero-point calibration (\( \sigma_{\Delta I} \sim 0.05 - 0.2 \)), the possible difference in the magnitude scale, and the intrinsic cosmic variance, we do not consider this difference to be significant.

We model the galaxy counts of Fig. 8 following the method described by Cole, Treyer, & Silk (1992). They give the equations of the volume element, the comoving distance and the luminosity distance of the objects for three cosmologies (\( \Omega_0 = 1 \), Einstein de Sitter; \( \Omega_0 = 0.2 \) Open; \( \Omega_0 = 0.2 \), \( \Lambda = 3(1 - \Omega_0)H_0^2 \) Flat, a factor \( c/H_0 \) is missing in their equation of the volume element for the flat \( \Lambda \) universe). Yoshii (1993) also details a similar method. The luminosity function (LF) is chosen to be similar to the CFRS for which LFs have been measured separately for blue and red galaxies (Lilly et al., 1993). Here we approximate the LF by its red component. The Schechter parameterization \( \phi(M) \) is used (Schechter, 1976),

\[
\phi(M) = \frac{0.41n_10}{M^* - M} \times \exp(-10^X),
\]

where \( M \) is the absolute magnitude in the \( V \) or \( I \) band, and \( \phi^*, M^* \) and \( \alpha \) are the Schechter parameters (Here, \( M^*_I = -21.5 \), \( \phi^* = 0.004 \), \( \alpha = -1.0 \)). \( K \) corrections are determined using 13-Gy-old elliptical galaxy template spectra from the PEGASE atlas (Fioc and Rocca-Volmerange, 1997), between redshifts \( 0 < z < 2 \). As already noted by many authors, this simple model does not provide a satisfactory fit to the number counts at faint and bright magnitudes simultaneously for any cosmologies in the \( V \)-band. A better fit would include a more realistic luminosity function accounting for both the red and blue galaxy populations, and for either a density or a luminosity evolution (see section 6.1). As our purpose here is not to model the number counts, we limit ourselves to this partial model.

Figure 8 shows that our UHSK number counts deviate from the predicted counts in non-evolving Einstein-de Sitter and open universes at \( I \gtrsim 21 \) and at \( V \gtrsim 22 \). Postman et al. (1998) observed a clear departure from these two cosmological models in their \( I \) counts using the no-evolution model of Ferguson & Babul (1998) (FB). All other surveys displayed in both panels of Figure 8 (Arnouts et al., 1996; Cowie et al., 1988; Driver et al., 1994; Gardner et al., 1996; Postman et al., 1998; Woods and Fahlman, 1997; Mamon, 1998; McCracken et al., 2000a) have the same behaviour, except for the \( V \) number counts of Cowie et al.
Fig. 8. Comparison of our UH8K galaxy counts in $V$ and $I$ with the results of Arnouts et al. (1999), Cowie et al. (1988), Drivers & Phillips (1994), Gardner et al. (1996), Postman et al. (1998), and Woods & Fahlman (1997), Mamon (1998), and McCracken et al. (2000a). Stars counts (solid line) are given according to the Bahcall model of the Galaxy. The vertical dotted line gives the limiting magnitude below which the star/galaxy classification is reliable (Fig. 7). Galaxy number counts are given for three cosmologies in $V$ and $I$ bands (cf text). The counts are in marginal agreement with a no-evolution flat $\Lambda$ universe.

(1988), which agree well with the Einstein-de Sitter model at $V \leq 22$ and deviate only at fainter magnitudes.

In contrast, Figure 8 shows that the non-evolving flat $\Lambda$ universe model provides a marginal agreement with our UH8K galaxy number counts in the $I$ band at our magnitude limit of $I \approx 22.5$. In fact, most surveys displayed in the right panel of Fig. 8 agree with this cosmological model at $I \lesssim 22$, as expected from the results of the CFRS (Lilly et al., 1996), where giant red galaxies evolve little in the redshift interval $0 - 1$. In Fig. 8, the deviations from the non-evolving flat $\Lambda$ universe occur in dataset which probe the faintest magnitudes, near $I \approx 24$. Our sample is not deep enough to show a departure from this cosmological model. Lidman et al. also find that their $I$ number counts (not shown in Fig. 8) are compatible with a no-evolution flat $\Lambda$ universe (Lidman and Peterson, 1996) out to $I \approx 21$, whereas they deviate from the evolution model of Yoshii (1993) (this model uses a dwarf galaxy blue LF, which yields very different $K$ corrections at faint magnitudes compared to a no evolution model). From the mentioned surveys, there are indications that evolution should be used in the modeling of the $I$ counts at $I > 22$, where significant departures from a non-evolving distribution occur.

There is also marginal agreement of most $V$ number counts displayed in the left panel of Fig. 8, including our UH8K data, with a non-evolving flat $\Lambda$ universe model. The deviations from the model occur in a wider range of $V$ magnitude, namely at $V \gtrsim 22 - 24$, depending on the data set, and the deviation is greater than for the $I$ counts. This may be partly explained by the fact that the $V$ number counts are more sensitive to evolution of the blue galaxy population than the $I$ counts.

4.3. Galaxy colours

Figure 9 shows histograms of galaxies and stars versus $V - I$ colours. For galaxies, histograms are given for three limiting magnitudes, $I < 20$, $I < 21$, and $I < 22.5$. The corresponding median $V - I$ colours are 1.45, 1.57, and 1.38. Figure 10 shows $V - I$ colours vs $I$ magnitudes for the sample of $\sim 30,000$ detected galaxies. A vertical line shows the $I$-band completion limit $I = 22.5$ and an oblique line shows $V - I$ colour limits accessible due the $V$-band completion limit of $V = 23.5$. There is no visible trend towards a strong colour evolution of the galaxies with their magnitudes, but a robust conclusion is not possible because the $I$ sample is depleted in red objects. A natural
Table 4. Differential $V$ and $I$-band galaxy counts (see Fig. 8).

| $V$ | $N$  | $\sigma_N$ | $I$ | $N$  | $\sigma_N$ |
|-----|------|------------|-----|------|------------|
| 15.75 | 1.4  | 1.4        | 15.75 | 29.8  | 6.5        |
| 16.25 | 4.3  | 2.5        | 16.25 | 21.3  | 5.5        |
| 16.75 | 10.2 | 3.8        | 16.75 | 45.4  | 8.0        |
| 17.25 | 20.3 | 5.4        | 17.25 | 103.6 | 12.1       |
| 17.75 | 36.2 | 7.2        | 17.75 | 183.1 | 16.1       |
| 18.25 | 69.6 | 10.0       | 18.25 | 330.8 | 21.7       |
| 18.75 | 146.4 | 14.6      | 18.75 | 533.9 | 27.5       |
| 19.25 | 236.3 | 18.5      | 19.25 | 968.4 | 37.1       |
| 19.75 | 406.0 | 24.3      | 19.75 | 1434.2 | 45.1       |
| 20.25 | 656.9 | 30.9      | 20.25 | 2355.7 | 57.8       |
| 20.75 | 964.2 | 37.4      | 20.75 | 3794.2 | 73.4       |
| 21.25 | 1571.8 | 47.7     | 21.25 | 5626.0 | 89.3       |
| 21.75 | 2531.7 | 60.6     | 21.75 | 7626.8 | 104.0      |
| 22.25 | 4058.5 | 76.7     | 22.25 | 10312.0 | 121.0     |
| 22.75 | 6219.1 | 95.0     | 22.75 | 13972.8 | 140.8     |
| 23.25 | 9991.9 | 120.4    | 23.25 | 15936.6 | 150.4     |
| 23.75 | 15665.8 | 150.7   | 23.75 | 12284.4 | 132.0     |
| 24.25 | 16725.8 | 155.7   |         |        |            |
| 24.75 | 9894.8 | 119.8    |         |        |            |

Fig. 9. Histogram of galaxy counts (solid line) from top to bottom $I < 22.5$, $I < 21$, $I < 20$ and star counts (dotted line) vs $V−I$ colour. The star counts are scaled up by an order of magnitude. Only stars brighter than $I < 19$ are included.

although arbitrary value to divide red galaxies from blue galaxies is the median of the histogram with $I < 22.5$ in Fig. 8 located near $V−I = 1.4$. In the rest of the paper red galaxies will be those having $V−I > 1.4$ and blue galaxies will be those having $V−I \leq 1.4$.

5. Analysis

5.1. Estimation of $\omega(\theta)$

The 2-point angular correlation function $\omega(\theta)$ is calculated by generating samples of random points covering the same area and having the same number as the galaxy sample. We use the estimator $W(\theta)$ defined by Landy & Szalay [1993] (hereafter LS), which has the advantage of reduced edge effects and smallest possible variance:

$$W(\theta) \equiv W = \frac{DD - 2DR + RR}{RR},$$

where $DD$ is the number of galaxy-galaxy pairs, $DR$ the number of galaxy-random pairs, and $RR$ is the number of random-random pairs, all of a given angular separation $\theta$. Following Roche [1996, 1999], we set a logarithmic binning for the separation defined as $\Delta \log(\theta) = 0.2$. The numerical approach of LS is used to calculate $DD$, $DR$ and $RR$. If one defines the variables $d$ and $x$ as

$$d = \frac{DD}{G_p(\theta)n(n-1)/2},$$

$$x = \frac{DR}{G_p(\theta)n^2},$$

then eq. [8] can be re-written as

$$W = d - 2x + 1.$$
function is measured), LS also define $G_t(\theta)$, the probability of finding two neighbors both at a distance $\theta \pm d\theta/2$ of one given object.

$$G_t(\theta) = < n_t(\theta) > / [n(n-1)(n-2)/2],$$  \hspace{1cm} (13)

where $< n_t(\theta) >$ is the average number of unique triplets. $G_t(\theta)$ is necessary to evaluate the random errors (cf section 5.3).

5.2. Modeling of $\omega(\theta)$, $\xi(r)$ and $r_0$

The canonical parameterizations of the two-point spatial correlation function $\xi(r)$ (Phillips et al., 1978) and of the angular correlation function $\omega(\theta)$ (Peebles, 1980) are

$$\xi(r, z) = \left( \frac{r/\theta_0}{1 + z} \right)^{3+\delta} \text{ and } \omega(\theta) = A_w \theta^{-\gamma}$$  \hspace{1cm} (14)

where $r$ is the comoving distance, $\theta_0$ the correlation length at $z = 0$, $\theta$ the angular separation in radian, $A_w$ is the amplitude of angular correlation function, $\gamma$ and $\delta$ are the slopes ($\delta = \gamma - 1$) and $\epsilon$ is a parameter characterizing the evolution of clustering with the redshift $z$. If $\epsilon > 0$ the clustering evolves in proper coordinates, if $\epsilon = 0$ the clustering is constant in proper coordinates hence increases in an expanding universe, if $\epsilon = -1.2$ the clustering is constant in comoving coordinates. The comoving correlation length at a redshift $z$ is related to $\theta_0$ by

$$r_0(z) = \theta_0 (1 + z)^{-3(3+\epsilon-\gamma)/\gamma}.$$  \hspace{1cm} (15)

Given eq. (14) and the galaxy redshift distribution $N(z)$, one can relate $\omega(\theta)$ and $\xi(r)$:

$$\omega(\theta) = C \frac{r_0(z_{\text{peak}})}{r_0} \theta^{1-\gamma} B(\epsilon),$$  \hspace{1cm} (16)

$$B(\epsilon) = \left( \frac{c}{H_0} \right) \gamma^{-1} \int_0^\infty \frac{r_d(z)^{1-\gamma} N(z)^2}{g(z) \left( 1 + z \right)^{3+\epsilon} \theta} \, dz \times \left[ \int_0^\infty N(z) \, dz \right]^{-2},$$  \hspace{1cm} (17)

$$N(z) = \frac{\pi}{180} \int_{z_i}^{m_2} \sum_i \phi_i(M, z) \frac{dV}{d\omega},$$  \hspace{1cm} (18)

$$g(z) = \left( 1 + z \right) \left( \frac{1}{1 + \Omega_0 z} \right) \left( \Lambda = 0 \right),$$  \hspace{1cm} (19)

$$g(z) = \left( 1 + z \right) \left( \frac{1}{\sqrt{\Omega_0 (1+z)^3} + \Omega_0 + 1} \right) \left( \Lambda + \Omega_0 = 1 \right),$$  \hspace{1cm} (20)

$$C = \sqrt{\frac{\pi}{\Gamma(\gamma-1/2)}} \frac{\Gamma(\gamma/2)}{\Gamma(\gamma/2)} \approx 3.68.$$  \hspace{1cm} (21)

Here $r_d(z)$ is the angular diameter distance, $dV/d\omega$ is the comoving volume element, both given for three cosmologies in the appendix of Cole, Treyer and Silk (1992). $\sum_i \phi_i(M, z)$ is the luminosity function, whose definition might be dependent on different spectral type $i$ evolving with $z$, and $\Gamma$ is the gamma function. The value of $C$ is given for a typical value of $\gamma = 1.8$ (Peebles, 1980). Equations (13) to (21) allow to make a direct derivation of $r_0(z_{\text{peak}})$ from $A_w(\Delta m)$, where $z_{\text{peak}}$ if the peak of the redshift distribution of the galaxies in the sample defined by the interval of apparent magnitude $\Delta m$:

$$r_0(z_{\text{peak}}) = \left[ \frac{A_w(z_{\text{peak}})}{C B(\epsilon)} \right]^{1/\gamma}.$$  \hspace{1cm} (22)

$A_w(\Delta m)$ is rewritten as $A_w(z_{\text{peak}})$.

5.3. Estimation of errors

In the past few years, considerable theoretical efforts have been devoted to the calculation of errors in the estimation of $\omega(\theta)$. The errors can be divided into two categories: (1) the random errors; and (2) the systematic errors due to the various observational biases in the data. The systematic errors are caused by false detections, star/galaxy misidentifications, photometric variations and astrometric errors. The random errors are induced by the finite area of the survey and depend on the geometry and the size of the sample.

5.3.1. Random errors

Until recently, a Gaussian approximation for the distribution of the galaxies was assumed to calculate the errors on $\omega(\theta)$. However, the distribution of the galaxies is known to depart significantly from a Gaussian distribution on small scales. A finer approach would be to include the possible correlations of the data into the error analysis. This has been done by Bernstein (1994) on the LS estimator $W(\theta)$. Bernstein derives a formal solution to the random errors for the case of a hierarchical clustering universe in the limits $n \gg 1$ (number of galaxies in the sample), $W \ll 1$, and $\theta \ll$ angular size of the sample:

$$\left( \frac{\Delta W}{W} \right)^2 = 4 \left[ 1 - 2 q_3 + q_4 \right] W_{\theta_{\text{max}}} + \frac{4}{n} \left[ W_{\tau}(1 + 2 q_3 W) + q_3 - 1 \right] + \frac{2}{n^2} \left[ (G_p^{-1} - 1) \right] \frac{1 + W}{W^2 - W^{-1} - 1},$$  \hspace{1cm} (23)

where the parameters $q_3$ and $q_4$ are measured by Gaztañaga (1994). They are related to the hierarchical amplitudes $s_3$ and $s_4$ ($s_n \equiv \omega_n > /\omega_2 > n^{-1}$, where $\omega_n$ are the n-point angular correlation functions), by $q_3 \simeq s_3/3$ and $q_4 \simeq s_4/16$ (Gaztañaga, 1994). $s_3$ and $s_4$ have been derived by Gaztañaga (1994) and Roche & Eales (1993) from the APM catalogue (Maddox et al., 1990a); $s_3 \simeq 4$ and $s_4 \simeq 50$ at $\theta \simeq 0.1^\circ$, the scale at which the angular-correlation function is well measured in the APM catalogue (Maddox et al., 1990b); therefore $q_3 \simeq 1.3$ and $q_4 \simeq 3$. $W_{\tau}$ ($\tau$ for ring) is the 3-point angular correlation for triplets of galaxies defined by 2 galaxies at a distance in the interval $[\theta, \theta + d\theta]$ from the 3rd galaxy. In principle, $W_{\tau}$ is marginally greater than $W(\theta)$ as defined
in eq. (23), but \(W_r \approx W\) is a fair approximation. \(W_{\theta_{\max}}\) is the average value of the angular correlation function at the largest angular separation of the sample. This quantity is not directly accessible because the estimator \(W\) is biased by finite volume errors at separations similar to the size \(r_0\) in the calculation of \(V_{\text{r.m.s.}}\).

Dividing our sample into 8 sub-samples (one separation at mid-declination and three separations in right ascension) and measure the LS estimator \(W\). Then, assuming a power-law whose slope is set at the small angles we extrapolate the value \(W_{\theta_{\max}}\) for each sub-sample. Finally, \(W_{\theta_{\max}}\) is obtained as the average over the 8 sub-samples. Subdividing the sample into 8 sub-samples also allows to measure the error on \(W\) independently at all scales (the largest angular separation being a quarter of the largest full survey separation), by simply taking the variance over the 8 sub-samples. The resulting variance largely underestimates the variance defined in eq. (23).

5.3.2. Systematic errors

The cosmic bias or integral constraint: The measurement of \(W_{\theta_{\max}}\) provides the cosmic bias \(b_W\) as

\[
b_W(\theta) \simeq (3 - 4 q_3 - W(\theta)^{-1}) W_{\theta_{\max}}. \tag{24}
\]

\(\theta\) (Colombi, priv. comm. 1999). This bias can be corrected in the calculation of \(W(\theta)\) in the form of an additive factor IC. At small angular separations, \(b_W \simeq - W_{\theta_{\max}}/W\). This negative bias is very small but becomes comparable to \(W\) when \(\theta\) approaches the angular size of the sample. The usual way of correcting for the cosmic bias is to fix a slope for the angular correlation function and to find the constant value of IC which minimizes the \(\chi^2\) fitting to the data. One may point out that the cosmic bias becomes non-negligible only when the errors \(\Delta W/W\) of the LS estimator given by eq. (23) are large. The smallest scale at which \(b_W\) is \(\gtrsim 10\%\) is \(\theta \gtrsim 3\), which corresponds to the last 2 points in all curves plotted in Figures 12 and 13. In the interval \(17 < I < 21\) for example, \(b_W \simeq -0.09\). However, the random errors at this scale are also significant, \(\Delta W/W \approx 12\%\), which gives little weight to these points in the least-square fits of \(W(\theta)\).

We therefore consider that the cosmic bias has negligible impact on our reported slope and correlation amplitude, and we chose to ignore the cosmic bias in order to avoid introducing a prior information on the slope of \(W(\theta)\).

Misidentified stars: Because stars are uncorrelated on the sky as shown on Fig. 1, the stars fainter than \(V > 22\) and \(I > 21\) which are not removed from the catalogue dilute the clustering present in the galaxy correlation, i.e. decrease the amplitude of \(\omega(\theta)\). The usual way of correcting for this bias \cite{Postman1999, Woods1981} is to apply a star dilution (multiplicative) factor \(D_{\text{star}}\) to the parameterized amplitude \(A_{\omega}\).

\[
D_{\text{star}} = \left( \frac{N_{\text{obj}}}{N_{\text{obj}} - N_{\text{star}}} \right)^2,
\]

where \(N_{\text{obj}}\) is the number of objects in the galaxy samples, and \(N_{\text{star}}\) is the number of stars predicted by the Bahcall model of the Galaxy \cite{Bahcall1980}. For \(V < 22\) and \(I < 21\), \(N_{\text{star}}\) is given by the classification efficiency of 95% of SExtractor, namely the upper value is 5% of the number of stars detected, so \(D_{\text{star}} < 1.1\). The values of \(D_{\text{star}}\) for fainter limiting magnitudes are given in Table 3.

Masking: Although the SExtractor programme is very good at avoiding false detections, it is sometimes tricked by the diffraction patterns and large wings of bright stars as would be any code using an isophotal threshold for detection. Because such false detections are strongly clustered, they increase the correlation amplitude at scales corresponding to the angular size of the false structure. To prevent the systematic patterns which could be introduced by false detections, we define two masks, one covering the bad pixels, columns and regions, and one covering all stars brighter than \(V < 15\) (from the HST Guide Star Catalog). The second mask is made of four empirical components, (1) a central disk whose radius is defined by an exponential law as a function of magnitude \((\text{radius} = 4969 \exp[-0.378M_{\text{r.m.s.}}]\) pixels), (2) a vertical rectangle covering the bleeding streak, whose length is an exponential function of magnitude \((\text{bleed} = 1.28 \times 10^8 \exp[-0.8M_{\text{r.m.s.}}]\) pixels), (3) and (4) inclined rectangles (at 38.5° and 51° of the vertical axis) covering the diffraction spikes, also following exponential law of the magnitude \((\text{spike} = 5292 \exp[-0.315M_{\text{r.m.s.}}]\) pixels). The masked regions are partially visible in Fig. 1 because only bright stars show large wings and the low density of objects does not permit one to distinguish “true” empty regions from masked regions. We apply the same two masks to the random realizations for the evaluation of LS estimator \(W(\theta)\) in section 6.1.

Photometric errors: Two kinds of photometric errors may be present: the random errors or photon noise called \(\sigma_M\), and the residual calibration errors in the coefficients \(A_V\), \(A_I\), \(k_V\), \(k_I\) and the zero-points \(V_0\) and \(I_0\). Note that the errors given in Table 3 called \(\sigma_{\Delta V}\) and \(\sigma_{\Delta I}\) include both the random and calibration errors. It is difficult but necessary to evaluate quantitatively the two kinds of errors because they have opposite qualitative effects on the angular correlation function.

The random errors can be evaluated from Table 3. It is clear that at bright magnitudes, the calibration errors dominate while random errors dominate at faint magnitudes. A random error in a galaxy apparent magnitude is equivalent to an increase of the possible volume in which...
that galaxy lies, i.e. it is equivalent to a convolution of the de-projected distance interval. Hence, the random error erases the clustering present in the sample. It is difficult to evaluate directly the decrease in the amplitude of \( \omega(\theta) \) due to the random errors because it is impossible to disentangle it from a real variation of the spatial galaxy clustering. Nevertheless, one can follow a simple argument to estimate how random errors affect the measurement of \( \omega(\theta) \).

First, assume that the galaxy number counts follow a power-law \( \log N = \alpha \text{ mag} + \text{cnst} \) so the relative error is \( \Delta N/N = (\alpha/\log e) \Delta \text{mag} \). An extreme case is to consider that all the galaxies with a magnitude error superior to the magnitude bin for which \( \omega(\theta) \) is evaluated (~ 0.5), are uncorrelated to the sample actually falling in the bin. This is an extreme case because many of the galaxies with the large error in magnitude do belong to the bin. In that case, these galaxies would have a very similar effect on the amplitude of \( \omega(\theta) \) as if they were stars. So the multiplicative diluting factor \( D_{\text{gal}} \) of the random photometric error would be,

\[
D_{\text{gal}} = (1 - (\alpha/\log e) \Delta \text{mag})^{-2},
\]

where \( \Delta \text{mag} \) is the magnitude error and \( \alpha \) is the slope of the galaxy number count power-law. Taking the best fit slope \( \alpha \simeq 0.4 \) (see Fig. 3 and Table 3), a typical magnitude error of 0.15 (see Table 3) leads to a dilution factor of \( D_{\text{gal}} \simeq 1.3 \), of order of the star dilution factor \( D_{\text{star}} \) given in Table 3. This estimate of \( D_{\text{gal}} \) is an indicative upper limit, and cannot be used to correct for the dilution due to random errors in the magnitude of the galaxies because the prior condition is that these galaxies are uncorrelated. This assumption might not be true, and the correction would then artificially increase the amplitude of the correlation function.

We now evaluate the calibration error budget. Because the largest airmass difference in \( V \) is 0.267, and 0.028 in \( I \), even a 50% error on \( A_V \) and \( A_I \) would not produce more than \( \Delta V \sim 0.015 \) and \( \Delta I \sim 7 \times 10^{-4} \). If we assume that the chip-to-chip error on \( k_V \) is given by the difference between the values of the synthetic sequence and the measurement of Cuillandre in Table 3 (this is certainly not the case for \( k_I \), because Cuillandre’s value is too low) then in the most extreme colours \( (V - I) \sim 4 \) (only a very small fraction of our sample), the resulting magnitude difference would be \( \Delta V \sim 0.008 \). The case of \( k_I \) is not clear, although it seems reasonable to assume that the error cannot be more than ten times the error \( \Delta V \), so \( \Delta I < 0.08 \). The residual systematic errors in the zero-points have been evaluated in section 3.3 to be \( \sigma \simeq 0.05 \). Combining all these mentioned sources of calibration errors, one finds a value of 0.053 in \( V \) and an upper value of 0.094 in \( I \).

The residual photometric errors have an opposite effect on \( W(\theta) \). Namely, they introduces CCD-to-CCD variations in the galaxy number counts wrongly interpreted by the correlation analysis as intrinsic clustering on a scale given by the angular size of the individual CCD chips, thus artificially increasing the amplitude of \( \omega(\theta) \) on these scales. Geller, de Lapparent & Kurtz (1984) showed that plate-to-plate systematic variations of more than 0.05 mag introduced in the Shane-Wirtanen catalogue would produce a flattening of the correlation function and an artificial break at a scale corresponding to the plate size. For that reason, we limit our measurement of the angular correlation to \( \theta < 400'' \simeq 0.1^\circ \), corresponding to the smallest dimension of the individual CCD’s. We point out that the combined effect of random and zero-point errors would be to flatten artificially the slope of \( \omega(\theta) \), as Geller et al. demonstrated.

**Astrometric errors:** Small scale astrometric errors are likely to become significant when the bin size of \( \omega(\theta) \) is of the order of the error. The trivial method to avoid such contamination is to limit the analysis to bins greater than the errors, i.e. greater than 0.5" in our case. When one builds a mosaic survey combining overlapping patches of the sky, systematic astrometric errors may come into play: the number of objects may be artificially higher or smaller in overlapping regions just because of misidentifications. This would induce a similar effect on the amplitude of correlation to the zero-point errors at an angular scales of the order of the field size. However, a comparative analysis of the number counts of overlapping regions with other parts of the field does not show any significant bias toward a higher number of objects in the overlapping regions. We therefore consider that our astrometric errors have a negligible effect on \( \omega(\theta) \), and we limit its calculation to \( \theta > 1'' \).
Table 5. Star dilution correction factor $D_{\text{star}}$ in $V$ and $I$ bands

| $V$ | $D_{\text{star}}$ | $I$ | $D_{\text{star}}$ |
|-----|-----------------|-----|-----------------|
| 22.25 | 1.08 | 21.25 | 1.23 |
| 22.75 | 1.11 | 21.75 | 1.20 |
| 23.25 | 1.10 | 22.25 | 1.17 |
| 23.75 | 1.09 | 22.75 | 1.15 |
| 24.25 | 1.08 | 23.25 | 1.13 |

6. Results

First, we tested the reliability of our code for measuring the LS estimator of $\omega(\theta)$ on the Zwicky catalogue. The result is consistent with that of Peebles (1974). We also used a deep catalogue (courtesy of Roukema, priv. comm. 1999) and found good agreement with its $\omega(\theta)$ measurement.

Figure 1 shows the result of our angular correlation code on the sample of stars brighter than $I < 21$. We limit the calculation of $W(\theta)$ at 0.1 degrees because of the reasons invoked in section 5. The function is always consistent with a random distribution. The weak positive signal might be a sign of misclassification of galaxies or simply small over-densities. The LS estimator (eq. [12]) is then measured, and found good agreement with its $\omega(\theta)$ measurement.

A final check on the code was done by Colombi (priv. comm. 1999) using a count-in-cells routine. The results showed that the quality of the dataset allows to measure higher orders of the distribution of galaxies (skewness & kurtosis). The measurements of the angular correlation in the interval $17 < I < 21$ gave consistent results with the LS estimator.

Here, we only show the correlation function in the $I$ band. We also measured $W(\theta)$ on the $V$-band map in the magnitude intervals $17 < V < 21.5$, $17 < V < 22$, $17 < V < 22.5$, $17 < V < 23$, and $17 < V < 23.5$. The values of the amplitude $A_W$ obtained in the $V$ band are very similar to the values obtained in $I$, but the average slope $\delta$ is $\approx 0.5 - 0.6$ in $V$, as compared to $\approx 0.8 - 0.9$ in $I$. Neuschaefer & Windhorst (1995) also measured slopes $\delta \approx 0.5$ in the $g$ and $r$ bands and $\delta \approx 0.7 - 0.8$ in the $i$ band.

6.1. Variation of slope versus magnitude

Recent ΛCDM models predict a decrease of the spatial correlation slope $\gamma$ for scales $< 10h^{-1}\text{Mpc}$ from $\gamma = 1.8$ at $z = 0$ to $\gamma \approx 1.6$ for $z \geq 1$ (Kauffmann et al., 1999). This implies a decrease of the slope $\delta = \gamma - 1$ of $W(\theta)$ at small angular scales and faint magnitudes. Observational evidences are poorly conclusive. Brainerd et al. (1999) report a steepening of the slope on small scales while Campos et al., 1995, Neuschaefer and Windhorst, 1995, Infante and Pritchett, 1995, and Postman et al. 1998 find the opposite effect. Other authors find no significant variations to the limits of their samples (Couch et al., 1993, Roche and Eales, 1993, Hudon and Lilly, 1996, Woods and Fahlin 1997). Figure 13 and Table 6 show no significant flattening of slope at faint magnitudes. The slope is compatible with $\delta = 0.8$ for all magnitude intervals. Our result is nevertheless consistent with the results of Postman et al. (1998) who find signs of a decrease only in their faintest bins, at $I > 22$, near and beyond our $I$ limit.

6.2. Variation of $A_W$ with magnitude

The choice of a galaxy luminosity function to model the decrease of $A_W$ with the limiting apparent magnitude is crucial because the behavior of $A_W$ is sensitive to both the parameterized characteristic absolute magnitude $M^*$ and the slope $\alpha$ (eq. [1]). We choose to use the luminosity function observed in the CFRS (Lilly et al. 1996), derived from 591 galaxies in the range $0 < z < 1$, keeping in mind that such a small sample of galaxies can only provide an indication of a general trend. Because both the CFRS sample and our sample have been selected in the $I$ band, we thus limit the possible biases due to the photometric sample selection.

Lilly et al. divide the CFRS sample into a red population (redder than an Sbc having rest-frame $[U - V]_{AB} = 1.38$, $[U - V]_{AB} \simeq [V - I]_{AB}$ at $z \sim 0.5$, $V_{AB} = V$, and $I_{AB} = I + 0.48$) and a blue population (bluer than an Sbc). The red galaxies show no density or luminosity evolution in the range $0 < z < 1$, whereas the blue galaxies
Recent measurements made from the CNOC2 analysis separates the luminosity evolution in the range 0 < z < 0.7, confirms the general observations of the CFRS, although the proposed interpretation is notably different. The CNOC2 analysis separates the luminosity evolution from the density evolution. Early and intermediate (red) galaxies show a small luminosity evolution in the range 0.1 < z < 0.7 (∆M* ≈ 0.5), whereas late (blue) galaxies show a clear density evolution with almost no luminosity evolution in the same redshift range, in apparent contradiction with the CFRS results.

We choose to adapt the CFRS LF to our sample, and we proceed as follows. Galaxies are separated into two broad spectro-photometric groups, the E/S0/Sab (called red) and the Sbc/Scd/Irr (called blue), using the median colour V − I = 1.4 (see section 4.3). The red group has a non-evolving luminosity function with parameters $\phi^+ = 0.0148 h^3$ Mpc$^{-3}$, $M_\star^+ = -21.5 + 5 \log 10h$, and $\alpha = -0.5$ (eq. [4]), and the blue group has a mild-evolving luminosity function with parameters $\phi^+ = 0.015 h^3$ Mpc$^{-3}$, $M_\star^- = -21.56 + (1 - e^{-2z}) + 5 \log 10h$, and $\alpha = -1.07$. The factor $1 - e^{-2z}$ equals 0 for $z = 0$ and $z \approx 1$ for $z \geq 1$ and mimics the observed smooth brightening of $M_\star^-$ with redshift.

We integrate eq. (23) in the different apparent magnitude intervals listed in Table 6 and obtain $N(z)$ for three cosmologies. The $K$ corrections are computed from tem-
Fig. 12. Plots of Log $W(\theta)$ spaced by 0.5 dex (symbols; see also Table 6) and best-fit curves ($A_W$ and $\delta$ of Table 6) as dotted line. From top to bottom, $17 < I < 20$ (k=5), $17 < I < 20.5$ (k=4), $17 < I < 21$ (k=3), $17 < I < 21.5$ (k=2), $17 < I < 22$ (k=1), $17 < I < 22.5$ (k=0)

Fig. 13. Plots of the differences of the LS $W(\theta)$ and the best-fit $A_W^0 \theta^{-0.8}$ (dotted lines). The curves are spaced by 1 dex for sake of clarity. Same magnitude intervals as Fig. 12

plates of E (9 Gy) for the red group and Sd (13 Gyr) for the blue group from the PEGASE atlas (Fioc and Rocca-Volmerange, 1997) and are shown in Fig. 14. The choice of a given atlas is not benign, as Galaz (1998) shows that $K$ corrections can vary by 50% at $z \sim 1$ when comparing the PEGASE atlas with the GISSEL atlas (Bruzual and Charlot, 1993), leading to significant differences in $N(z)$.

Figure 15 shows $N(z)$ for red and blue objects having $I < 22.5$, for three cosmologies: Einstein-de Sitter $\Omega_0 = 1$ as a solid line, open universe $\Omega_0 = 0.2$ as a dashed line, and flat $\Lambda \Omega_0 = 0.2$ universe as a dotted line. One can note that red and blue galaxies show very different redshift distributions as expected from the different LFs. This should be kept in mind when we compare the different evolution of $A_W$ with magnitude for the red and blue samples. The resulting $N(z)$ used to model our sample is the sum of the $N(z)$ for the red and blue object distributions respectively. As our 2 colour samples suffer from differential incompleteness (see section 3.3), we normalized the relative number of blue and red objects to the observed ratio in the CFRS survey at the corresponding limiting magnitude.

Figures 16, 17, and 18 show the decrease of the amplitude of the correlation function corrected for star dilution $A_W^\text{corr}$ for the median I magnitude of the integrated and incremental intervals (Table 6); a fixed slope of $\delta = 0.8$ is used to measure the reference scale, which is taken a 1 degree. The data-points for the incremental intervals show larger error bars, but are consistent with the amplitudes for the integrated intervals. The measurements of Postman et al. (1998) and Lidman & Peterson (1990) are shown for comparison. We also plotted the expected curves for the three universes mentioned above, for each of the three values of the clustering parameter $\epsilon = -1.2$ in Fig. 16, $\epsilon = 0$ in Fig. 17, and $\epsilon = 0.8$ in Fig. 18. For each value of $\epsilon$, the theoretical curves are calculated with $\delta = -0.8$ and the best-fit spatial correlation length $r_{00}$ at $z = 0$, using eq. (15) and (22). These values along with the corresponding $\chi^2$ of the fit are listed in Table 8 (only the integrated intervals of magnitude are used for the fitting, 6 data-points). Note that in Fig. 16, 17, and 18 different values of $r_{00}$ shift the theoretical curves by constant values in the Y direction.

Several conclusions can be drawn from Fig. 16, 17, 18 and Table 8. We can always find a set $\Omega_0$, $\epsilon$ and $r_{00}$ which fits our data. A universe with $\Omega_0 = 0.2$ and $\Lambda = 0.8$ slightly favour null $\epsilon$, in good agreement with the results of Baugh et al. (1999) for semi-analytical models of biased galaxy formation. In contrast, Table 8 shows that Einstein-de Sitter universes favour positive $\epsilon$ (recall that $\epsilon = -1.2$ means no evolution in comoving coordinates, and $\epsilon = 0$ no evolution in physical coordinates), as obtained by Hudon & Lilly (1996) ($\epsilon = 0.8$) for the hierarchical clustering CDM model of Davis et al. (1985) in Einstein-de Sitter Universes. Third, positive values of evolution parameter $\epsilon$ give better fits to our observations (Fig. 18) than negative $\epsilon$. Moreover, comparison of the $r_{00}$ listed in Table 8 with the local values of $r_{00} \sim 4 - 8 h^{-1}$ Mpc at $z \simeq 0$ also suggest null to mild clustering evolution.

Finally, Table 8 gives the peak redshift $z_{\text{peak}}$ derived from the redshift distributions $N(z)$ (using the CFRS model luminosity function) for all magnitude intervals and for the three cosmologies. Using eq. (22), the values of $r_{00}(z_{\text{peak}})$ are computed for all $z_{\text{peak}}$, and can be compared to other results. At $z \simeq 0.5$, we measure a value of $r_{00}(z_{\text{peak}})$ in the range $3.4 - 3.7 h^{-1}$ Mpc, depending on the cosmological model and the evolution index $\epsilon$. The
Fig. 14. $K$ corrections for early-type and late-type galaxies in $V$ & $I$ band. We use the simplest hypothesis of non-evolving galaxy spectra over the range $0 < z < 2$.

Typical $1\sigma$ uncertainty on the values of $r_0(z_{\text{peak}})$ listed in Table 8 is $\sim 0.35$ $h^{-1}$ Mpc. The additional error originating from the uncertainty in the cosmology and in $\epsilon$ is estimated from Tables 8 and 9 to be $\sim 0.35$ $h^{-1}$ Mpc. By adding these errors in quadrature, we find an estimated total error in the correlation length $r_0$ of $\sim 0.5$ $h^{-1}$ Mpc.

If we assume a flat $\Lambda = 0.8$ cosmology, Table 8 gives $r_0(z_{\text{peak}}) \approx 3.5 \pm 0.5 h^{-1}$ Mpc at the peak redshift $z_{\text{peak}} \approx 0.58$ of the $I < 22.5$ survey. The corresponding value at $z_{\text{peak}} \approx 0.50$ is $r_0(z_{\text{peak}}) \approx 3.7 \pm 0.5 h^{-1}$ Mpc. Within the error bar, this result is in agreement with most other angular correlation measurements at $z_{\text{peak}} \approx 0.5$ (Postman et al., 1998; Hudon and Lilly, 1996; Roche and Eales, 1999; Woods and Fahlman, 1997).

If we compare with the direct spatial measurements, our result is closer to the CNOC2 results than those from the CFRS: Carlberg et al. find that the 2300 bright galaxies in the CNOC2 survey (Yee et al., 1996) show little clustering evolution in the range $0.03 < z < 0.65$ with $r_0 \approx 3.5 - 4.5 h^{-1}$ Mpc at $z \approx 0.5$, depending on the cosmological parameters (Carlberg et al., 2000); whereas Le Fèvre et al. measure $r_0 \approx 1.5 h^{-1}$ Mpc at $z \approx 0.5$ for 591 I-selected galaxies, implying a strong evolution from the local values ($r_0 \approx 4 - 8 h^{-1}$ Mpc at $z \approx 0$) (Lilly et al., 1995). As mentioned above, the small correlation length found in the CFRS survey may be due to the cosmic variance which affects small area surveys. On the other hand, neither the CNOC2 survey nor the CFRS survey detect an evolution in the slope $\gamma \sim 1.8$, in good agreement with our UH8K data.

Fig. 15. Redshift distributions $N(z)$ for red and blue objects assuming CFRS-like LF. The limiting magnitude is $I < 22.5$. The peaks of the red+blue distributions are normalized to 1000. The relative number of blue and red objects are normalized to the observed ratio in the CFRS survey.

Fig. 16. The amplitude of correlation $A^\text{star}_W$ for the UH8K data is plotted against the median $I$ magnitude for the same intervals as in Fig. 12 and 13 (filled symbols) and is compared to the results from other groups. The four filled squares with large error bars are the measurements for the incremental intervals, and the diamonds show the values for the integrated intervals (see also Table 7). Theoretical curves are calculated for $\epsilon = -1.2$ and the corresponding best-fit $r_{00}$ (listed in Table 8) obtained with $\delta = -0.8$, and for three universes: Einstein-de Sitter as solid lines, $\Omega_0 = 0.2, \Lambda = 0$ as dashed lines and $\Omega_0 = 0.2, \Lambda$ flat universe as dot-dashed lines. We use the bimodal CFRS luminosity function with mild luminosity evolution described in subsection 6.2.
curves. The corresponding best-fit $r_0$ are given in Table 8.

Fig. 17. Same as Fig. [14] but with $\epsilon = 0$ for the theoretical curves. The corresponding best-fit $r_0$ are given in Table 8.

Fig. 18. Same as Fig. [14], but with $\epsilon = 0.8$ for the theoretical curves. The corresponding best-fit $r_0$ are given in Table 8.

Table 9. Redshift $z_{\text{peak}}$ of the peak of the redshift distribution $N(z)$ and the corresponding best-fit correlation lengths $r_0(z_{\text{peak}})$ for different magnitude intervals and cosmologies. Here $\epsilon = 0.8$

| $I$ Magnitude Interval | Median magnitude | $z_{\text{peak}}$ | $r_0$ | $z_{\text{peak}}$ | $r_0$ | $z_{\text{peak}}$ | $r_0$ |
|------------------------|------------------|------------------|------|------------------|------|------------------|------|
| 17-20.0                | 19.356           | 0.295            | 3.98 | 0.295            | 3.89 | 0.295            | 4.39 |
| 17-20.5                | 19.807           | 0.325            | 3.88 | 0.325            | 3.80 | 0.330            | 4.26 |
| 17-21.0                | 20.281           | 0.355            | 3.78 | 0.365            | 3.67 | 0.385            | 4.07 |
| 17-21.5                | 20.724           | 0.390            | 3.65 | 0.425            | 3.52 | 0.440            | 3.90 |
| 17-22.0                | 21.166           | 0.455            | 3.50 | 0.485            | 3.34 | 0.510            | 3.70 |
| 17-22.5                | 21.617           | 0.505            | 3.37 | 0.565            | 3.16 | 0.575            | 3.53 |

6.3. Variation of $A_W$ with galaxy colour

We also calculate the variations of $A_W$ with depth for the blue and red sub-samples of our UHSK data, which are defined in subsection 4.3. A map of the 8986 red galaxies $(V-I > 1.4)$ with $I \leq 22$ is shown in Figure 19 (top panel); the 7259 blue galaxies $(V-I < 1.4)$ to the same limiting magnitude are plotted in the bottom panel of Figure 19. One can see that red objects are more clustered than blue objects, as partly reflected by the morphology density relationship (Dressler, 1980). Note that the surface density of the blue galaxies increases by a factor of $\sim 2$ with increasing right ascension. This is probably caused by a systematic drift in the photometric zero-point along the R.A. direction, which was not completely removed by the matching of the magnitudes in the CCD overlaps (see subsection 3.2). We then perform an angular correlation analysis on each colour-selected sample. For the blue sample, we introduce in the random simulations, prior to masking, the mean R.A. gradient measured from the data.

Figure 20 shows the decrease of $A_W$ for the red and blue galaxies to a limiting magnitude $I < 22.5$ (see section 3.3 & 4.3). In principle, the separation should be done on rest-frame colours and not on observed colours, but this requires prior knowledge of the redshift of the objects. The effect of using observed colours is to decrease the resulting angular correlation because galaxies of different intrinsic colours at different distances are mixed together. We use the same angular binning as in the previous analyses for consistency (subsections 6.1 & 6.2). Table 10 gives the median magnitude of the red and blue samples. The last interval given in Table 10 includes all 11,483 red galaxies ($I_{\text{med}} = 21.670$) and 20,743 blue galaxies ($I_{\text{med}} = 22.902$) fainter than $I > 17$ (to $V \sim 24$ and $I \sim 23$).

Note that the blue sample reaches fainter $I$ magnitudes than the red sample. As seen in the section 3.3, this is a selection effect due to the fact that only galaxies detected in the 2 bands are shown in the sample, and the blue sample is complete to $V \sim 24$. Thus at $I > 22.5$, the galaxies redder than $V-I > 1.5$ (in fact most of the red sample) show sparse sampling. Each interval in Table 10 is respectively complete for galaxies having $V-I < 3.25$, $2.5$, $2.15$. We emphasize that the last two intervals of the red sam-

Table 8. Best-fit values of the spatial correlation length $r_0$ for fixed $\epsilon$ and three cosmologies.

| $r_0$ | $\epsilon$ | Cosmology | $\chi^2$ |
|-------|------------|-----------|----------|
| $h^{-1}$ Mpc | $\Omega_0$ | $\Lambda$ |          |
| 3.53 ± 0.28 | -1.2 | 1 | 0 | 0.0115 |
| 3.49 ± 0.41 | -1.2 | 0.2 | 0 | 0.0125 |
| 4.11 ± 0.21 | -1.2 | 0.2 | 0.8 | 0.00676 |
| 4.43 ± 0.33 | 0 | 1 | 0 | 0.00499 |
| 4.38 ± 0.28 | 0 | 0.2 | 0 | 0.00367 |
| 5.03 ± 0.28 | 0 | 0.2 | 0.8 | 0.00232 |
| 5.31 ± 0.31 | 0.8 | 1 | 0 | 0.00269 |
| 5.19 ± 0.34 | 0.8 | 0.2 | 0 | 0.00218 |
| 5.85 ± 0.35 | 0.8 | 0.2 | 0.8 | 0.00233 |
Table 10. Median magnitude $I_{\text{median}}$ of the red and blue samples for the different cumulative $I$ magnitude intervals.

| Mag. interval | # red gal. | $I_{\text{median}}^{\text{red}}$ | # blue gal. | $I_{\text{median}}^{\text{blue}}$ |
|---------------|------------|----------------------------------|-------------|----------------------------------|
| 17-21         | 3379       | 20.212                           | 1854        | 20.212                           |
| 17-21.5       | 5057       | 20.711                           | 2934        | 20.741                           |
| 17-22         | 7069       | 21.055                           | 4589        | 21.219                           |
| 17-22.5       | 8986       | 21.351                           | 7259        | 21.739                           |
| >17           | 11483      | 21.670                           | 20743       | 22.902                           |

Fig. 19. Map of 7069 red galaxies with observed $V-I > 1.4$ (top) and 4589 blue galaxies with observed $V-I < 1.4$ (bottom) to $I < 22$.

Fig. 20. Same as Fig. 16. The galaxies of our sample are divided into red galaxies with $V-I > 1.4$ (filled octagons) and blue galaxies with $V-I \leq 1.4$ (filled triangles). The results for the full sample of Postman et al. (1998) (open squares) are shown for reference. Best-fit models are shown for a $\Lambda$ flat universe with $\epsilon = 0.8$ for red galaxies using CFRS red LF (solid line) and blue galaxies using CFRS blue LF with mild evolution (dashed line).
in Fig. 20, in the red sample (8986) compared to the blue sample (7259, see Table [1]) is caused by large random errors at the limit of the catalogues, as seen in section 5.3.2. These would tend to dilute the $A_W$ for the red sample. The detected increased clustering strength for the red sample over the blue sample is therefore a lower limit on the amplitude difference with colour. The apparent flattening of $A_W$ with $I_{\text{median}}$ for red galaxies in Fig. 20 may be due to the incompleteness of red objects at faint magnitudes as discussed above.

The difference in clustering amplitudes which we measure for our red and blue samples agrees with observations by Neuschaefer et al. (1995), Lidman & Peterson (1996) and Roche et al. (1996). Neuschaefer et al. find that disk-dominated galaxies (blue $V-I$) have marginally lower $A_W$ than bulge-dominated galaxies (red $V-I$) using HST multi-colour fields. Similarly, Roche et al. observe a 3r difference in $A_W$ for a sample divided into objects bluer or redder than $b-r = 1.64$. Lidman & Peterson see a weak difference between two samples separated by $V-I = 1.5$. Other authors don’t see any difference between blue and red-selected samples, such as Woods and Fahlman (1997) for a separation of $V-I = 1.3$, Brainard et al. (1993) for $(g-r) = 0.3$, Le Fèvre et al. (1996) in the spatial correlation length of the CFRS for rest-frame $(U-R)_{\text{AB}} = 1.38$, and Infante & Pritchet (1997) for $(J-F) = 1$. In all these cases excepting Infante & Pritchet, who used photographic plates, both the number of galaxies and the angular scale of the surveys are small. It might be possible that in these surveys cosmic variance hides a weak signal.

7. Discussion

7.1. Limber’s formula

Limber’s formula (written here as eq. [15] and [16]) relating $\omega(\theta)$ and $\xi(r)$ is strongly dependent on the shape of the redshift distribution $N(z)$ which depends on the characteristic absolute magnitude $M^*$ and slope $\alpha$ of the luminosity functions of the different types of galaxies (eq. [8]). Locally, these parameters cover a wide range of values with regard to the environment and the morphological types of the galaxies.

Segregating galaxies into red and blue samples based on observed colour, as we do here, is also a crude first step, and should rather be performed using intrinsic colour or, even better, spectral type (cf section 6.3). These in turn would require knowledge of the galaxy redshifts. Approximate redshifts can also be obtained along with spectral type for multi-band photometric surveys using photometric redshift techniques (Koo, 1999). Because none of the required functions and distributions are available for our UH8K sample, we emphasize that the reported results can only be taken as phenomenological, and all the comments on the deduced clustering must be taken with caution.

7.2. The cosmological parameters

Most authors take for granted that different cosmological parameters only lead to minor differences in the evolution of clustering, compared to the effects due to the uncertain luminosity function. Figure 14 to 20 do show that for a given luminosity function different cosmological parameters induce different values of $r_0$ and $\epsilon$. From our models, $r_0$ differs by more than 15% between the Λ flat and Open universes. These differences cannot yet be distinguished with the present data (up to $z \sim 1$). The dispersion between the different observations (Fig. 21) precludes any derivation of the cosmological parameters.

Given a CFRS luminosity function, the Λ flat universe gives the better fits to galaxy number counts, and clustering evolution of our sample ($\epsilon = 0 - 0.8$). This is in agreement with a current (though controversial) interpretation of recent type Ia supernovae results (Schmidt et al., 1998; Perlmutter et al., 1999). Notwithstanding the numerous modern methods to measure the cosmological parameters, the present analysis shows that future surveys containing 10^6 galaxies with known luminosity functions per galaxy type and redshift interval to $z \sim 1$ will be required to provide good constraints on cosmological parameters using this technique.

7.3. The evolution of clustering

Figure 21 shows the decrease of the amplitude of the angular correlation of our sample compared to most of the other recent measurements made in the I band (Brainard and Smail, 1998; Campos et al., 1993; Woods and Fahlman, 1997; Postman et al., 1995; Lidman and Peterson, 1996; Neuschaefer and Windhorst, 1995; McCracken et al., 2000). We applied a magnitude translation between Neuschaefer & Windhorst i magnitude and our I magnitude of $I = i - 0.7$.

In the magnitude range I=20–22, our results are in good agreement with most of these results except those of Campos et al, which have the highest amplitude, and on the low side, those of Lidman & Peterson and of McCracken et al., 3 times lower in amplitude. Postman et
Postman et al. observe a flattening of $A_W$ for scales $>1'$ and $I > 21$. The measurements of Brainerd & Smail extend the flattening of $A_W$ observed by Postman et al. to $I \sim 24$. We also find a possible flattening in the decrease of $A_W$ beyond $I \sim 21$. The most probable explanation for such high dispersion of about a factor ten between the different measurements of $A_W$ is the dependence of $A_W$ on the square of the number density. Cosmic variance may account for most of the discrepancies. The rest may be attributable to systematic errors of the estimators due to different spatial or magnitude samplings.

As pointed out by Neuschaefer & Windhorst (1995), a flattening of the slope $\delta$ (see eq. [14]) with the redshift or with apparent magnitude would lower the theoretical curve for $A_W$ derived with Limber’s formula (eq. [16]). Hence, smaller $A_W$ would still be compatible with a small $\epsilon$, or a high $\Omega_0$. In other words, clustering would grow faster at smaller scales than at larger scales. The flattening of the spatial correlation function is predicted by $N$-body simulations (Davis 1985; Kauffmann 1999a; 1999b). Neuschaefer & Windhorst parameterize the flattening of the slope $\gamma(z)$ with redshift $z$ as: $\gamma(z) = 1.75(1 + z)^{-C}$, where $C \simeq 0.2 \pm 0.2$. Postman et al. (1998) derive $C = 0.35 \pm 0.10$ with a slightly different parameterization: $\gamma(z) = 1.8(1 + z)^{-C}$.

8. Conclusions

In this paper, we present measurements of the angular correlation function for a sample of $\sim 20,000$ galaxies to $I < 22.5$, and $V < 23.5$ observed with the CFHT UH8K mosaic CCD camera over a contiguous area of $\sim 30' \times 90'$. The main conclusions are the following:

- The amplitude of the angular correlation function of the complete sample decreases monotonically through the entire range of magnitude intervals.
- The flattening in the decrease of the amplitude, observed by Postman et al., is marginally confirmed by our analysis.
- The best model to fit the evolution of the amplitude of our sample is the combination of the CFRS luminosity function with mild luminosity evolution of late-type galaxies and no evolution of early-type galaxies, a $\Lambda$ flat universe, a clustering evolution with $\epsilon > 0$, and a comoving correlation length of $r_0 \simeq 3.7 \pm 0.5 h^{-1}$ Mpc at $z \sim 0.5$. This in agreement with the local measurements of $r_0$ with the clustering evolution predicted by CDM hierarchical clustering models.
- Red-selected galaxies show higher amplitudes of correlation than blue selected galaxies.

The deep multi-band photometric surveys which are in preparation should determine whether these observational results on the evolution of clustering are due to an inadequate definition of the luminosity functions of the different types of galaxies or whether the actual clustering differences reflect different formation histories of disk-dominated vs bulge-dominated galaxies. Ideally, one would like to measure the spatial two-point correlation function for each galaxy type, and for different redshift intervals. The luminosity functions and their evolution with redshift must be measured accordingly in order to closely model the observed redshift distribution of the sources. Application of photometric redshift techniques (Arnouts, 2000 priv. comm.) to the deep extension of the EIS survey (La Costa & Renzini, 1999) (http://www.eso.org/science/eis/) should provide new constraints on these functions. Another deep survey which will also allow to address these issues is the LJT survey (Hickson et al., 1998), which will provide accurate redshifts to $\sigma_z \simeq 0.05$ and reliable spectral types for $\sim 10^6$ galaxies to $z \sim 1$. This will allow a more detailed study of the evolution of $A_W$. Note that the measured evolution of the clustering amplitude with redshift in these surveys might also provide useful constraints on the cosmological parameters.

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