GALAXY CLUSTERING TO B = 27^m

N. ROCHE, T. SHANKS, N. METCALFE and R. FONG
Department of Physics
University of Durham
South Road
Durham DH1 3LE, U.K.

1. Introduction — $\omega(\theta)$ as a Probe of N(z)

The angular two-point correlation function, $\omega(\theta)$, for galaxies can be used as a probe of their redshift distribution N(z) and, therefore, of galaxy luminosity evolution. Without redshift data, we can still observe the projection onto the two-dimensional sky of the three-dimensional clustering of galaxies. The autocorrelation of this projected distribution is described by $\omega(\theta)$. Observations have indicated that $\omega(\theta)$ follows a $\theta^{-0.8}$ power-law (Peebles 1980) and that the index of the power-law remains approximately constant to the faintest limits of photographic surveys (Jones, Shanks & Fong 1987).

The $\omega(\theta)$ amplitude is related to the amplitude of the 3-dimensional two-point correlation function $\xi(r)$ by means of an integration over N(z) using Limber's formula (see, for example, Phillipps et al. 1978). More specifically, Limber's formula incorporates an integration over $[N(z)]^2$ weighted by a term which decreases with increasing angular diameter distance — the result of such an integration being lower if either the variance or the mean of the redshifts is increased.

The intrinsic clustering strength of galaxies, as measured by $\xi(r)$, is parameterized by the correlation radius r_0, the distance at which the probability of finding another galaxy is twice that expected from a random distribution. Its value was estimated by Peebles (1980) from the Zwicky catalogue limited at B $\simeq$ 15 to be approximately 4.3 h^{-1}Mpc (where Hubble's constant $H_0 = 100$ h km/s^{-1}Mpc^{-1}). On going to fainter limits the variance and mean of the redshifts of galaxies in the sample would both be expected to increase, giving through Limber's formula a lower $\omega(\theta)$ for a constant r_0. Essentially, the wider the range of redshifts over which galaxies are distributed the more the observable clustering will be diluted by projection, and the clustering of more distant galaxies will contribute less to $\omega(\theta)$ as their r_0 will be projected to a smaller angle on the sky.

Hence the scaling of the $\omega(\theta)$ amplitude of the galaxies with survey depth will relate to the change with the magnitude limit of N(z). A given N(z) will produce a lower $\omega(\theta)$ amplitude for a lower q_0, because the angular diameter distances of the galaxies will be greater, although the dependence on q_0 only becomes significant when there are a high proportion of $z > 1$ galaxies. Any evolution with time which may also occur in the clustering of galaxies will also affect $\omega(\theta)$. However, the dominant effect on the correlation amplitudes is likely to be that of luminosity

H. T. MacGillivray et al. (eds.), Astronomy from Wide-Field Imaging, 635–643.

evolution, as this may greatly modify the redshift distribution at the faint magnitude limits considered here.

2. L* and ϕ* Evolution

The luminosity function of galaxies is usually represented as the Schechter function

$$\phi(L) = \phi^*(L/L^*)^{-\alpha} exp(-L/L^*)$$

parameterized by a characteristic luminosity L^*, a faint-end slope α and a density normalization ϕ^*. The evolution necessary to produce the high number counts may manifest itself as a brightening of L^* with increasing redshift — as in, for example, the models computed by Bruzual (1981). If ϕ^* and α remain constant while L^* evolves this is described as a pure luminosity evolution. In other words, it is assumed that the number of galaxies per unit of comoving volume is conserved, and that the giant and dwarf galaxies of the same morphological type evolve relative to their present-day luminosities by the same number of magnitudes at each value of the redshift.

In these models, the increase in star-formation rate with redshift would enable high redshift galaxies to be seen at brighter magnitudes and with bluer colours than if they were identical to nearby galaxies. Hence at a given magnitude, the effect of luminosity evolution is to enable galaxies to be seen out to greater redshifts, so giving higher number counts but at a *lower* $\omega(\theta)$ amplitude than a no-evolution model.

However, it has been claimed that N(z) is close to a no-evolution form (with a higher normalization) even at B ~ 23 - 24, the faintest limits reached at present by spectroscopic surveys (Lilly, Cowie & Gardner 1991), leading to suggestions that galaxy evolution is instead dominated by merging. The galaxies seen today would then have existed at earlier epochs as several sub-components, as in the models of e.g. Rocca-Volmerange & Guiderdoni (1990), and Broadhurst, Ellis & Glazebrook (1993). Hence at higher redshifts the comoving number density ϕ^* would be greater and the mean galaxy mass correspondingly less. The increased star-formation activity needed to explain the bluer colours of fainter galaxies (Tyson 1988; Metcalfe et al. 1991) would raise the luminosity per unit mass, so tending to compensate for the smaller masses of the sub-components. There would be little change in the blue-band L^* with redshift, and therefore merging could resemble a pure ϕ^* evolution for a blue-limited sample, giving an approximately no-evolution N(z) with a raised normalization. This would result in a $\omega(\theta)$ amplitude close to the no-evolution prediction, if we assume that the merging process itself does not greatly alter the intrinsic clustering of the galaxies. In this paper we therefore represent this type of evolution simply by a non-evolving model.

3. $\omega(\theta)$ Results

The $\omega(\theta)$ amplitude and scaling were first of all investigated for 4540 $B_{ccd} \leq 25.0$ galaxies observed on 12 CCD frames (total area 284 arcmin^2) at the INT. These data were published as number counts by Metcalfe et al. (1991b), and the calculation of $\omega(\theta)$ for the galaxies is described by Roche et al. (1993). The $\omega(\theta)$ was fitted with a function which gave a $\theta^{-0.8}$ power-law amplitude at one degree, corrected for 'integral constraint'. The result at our faint limit of $B_{ccd} = 25.0$ was $(4.214 \pm 2.044) \times 10^{-4}$ (field-to-field errors), consistent with the $\omega(\theta)$ results given by Efstathiou et al. (1991) for the deep CCD fields of Tyson (1988).

In addition we have a new result from the single deeper field described by Metcalfe, Shanks & Fong (1991a), which had approximately 24 hours exposure time at the INT. The $\omega(\theta)$ of the 1442 galaxies detected to $B_{ccd} = 27.0$ was similarly calculated (Fig. 1) and found to be only $(2.971 \pm 1.525) \times 10^{-4}\mathrm{deg.}^{-0.8}$ (errors from simulations).

Figure 2 shows our correlation amplitudes for a range of magnitude limits, compared with those obtained from other surveys. For details of these earlier results see Stevenson et al. (1985), Jones et al. (1987), Koo & Szalay (1984), Infante (1990) and Efstathiou et al. (1991). Our correlation amplitudes appear to be consistent with the photographic data to the faint limits of such surveys ($B \simeq 24$).

Figure 2 also shows the predictions of two models, differing only in the evolution with redshift of the characteristic galaxy luminosity L^*. A correlation radius of $r_0 = 4.3h^{-1}$Mpc and a value for q_0 of 0.05 were used. A model without luminosity evolution was computed using the k-corrections given by Metcalfe et al. (1991), which as far as the $\omega(\theta)$ scaling is concerned may approximately represent pure density evolution or an extremely merging-dominated model where N(z) has been hypothesised to have a similar form. Our evolving model, also described by Metcalfe et al. (1991b), used the pure luminosity evolution models calculated by Bruzual (1981), with an exponentially decreasing ($\mu = 0.5$) star-formation rate for the early type galaxies.

In a low q_0 Universe this pure luminosity evolution model can fit the number counts even to $B \simeq 27$ while still conserving the comoving number density of galaxies. With the Bruzual evolution, high redshift galaxies will appear in the sample quite suddenly on going to fainter

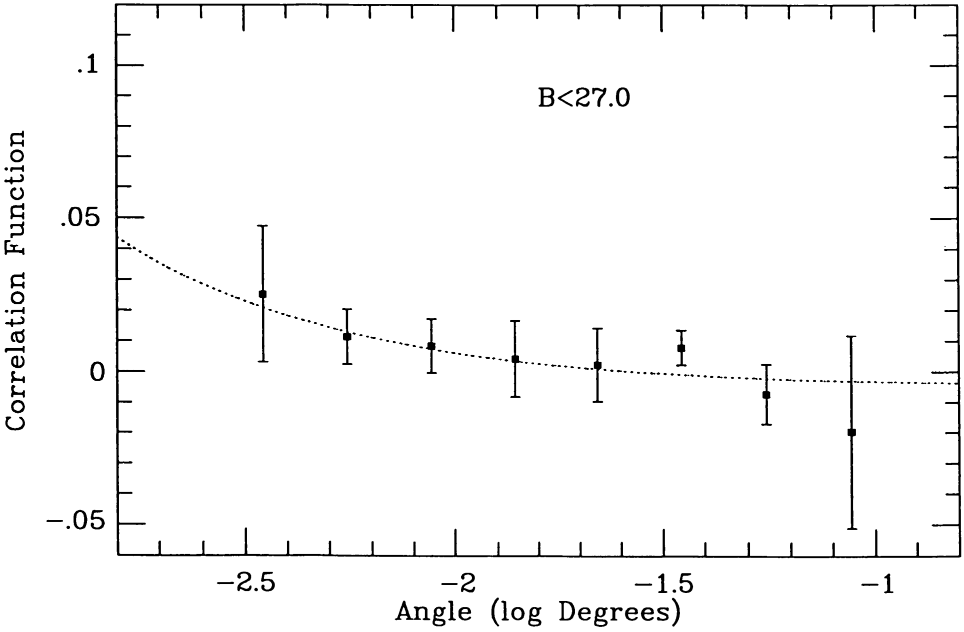


Figure 1. The angular correlation function of the $B_{ccd} \leq 27.0$ galaxies on the deep CCD frame, shown with error bars from simulations and the fitted $\theta^{-0.8}$ power-law.

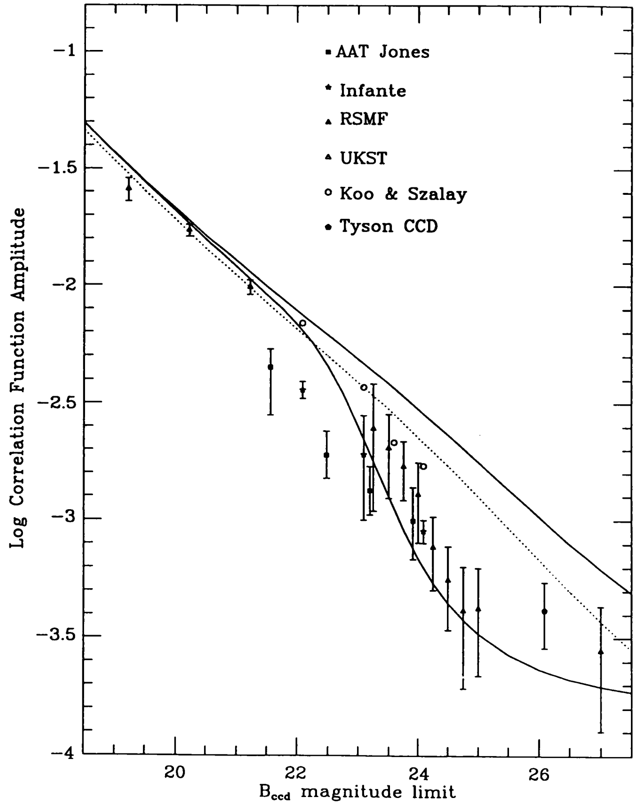


Figure 2. Estimates of the correlation function amplitude obtained from earlier photographic surveys and from our CCD frames, compared with the predictions of a non-evolving model (upper curve) and a model incorporating pure luminosity evolution (lower curve), over a range of blue magnitude limits (for $q_0 = 0.05$ and $z_{max} = 4$). The dotted line shows the effect of adding evolution of clustering to the non-evolving model.

limits, over a narrow range of magnitudes centred on B ~ 24, whereas if L^* does not brighten with redshift they will appear more gradually at B $\simeq$ 25. As a result of this, our PLE and no-evolution models predict $\omega(\theta)$ amplitudes differing by a factor of ~ 4 at B $\simeq$ 24 - 25, the magnitude range best covered (in terms of numbers of galaxies) by our CCD surveys.

It is clear that our correlation amplitudes do not follow the no-evolution scaling, being significantly lower at $B_{ccd} > 23$ and much closer to the Bruzual model predictions. Any conclusions about the redshift distribution on the basis of correlation amplitudes depend on the assumption, which is made in these models, that galaxy clustering is stable in proper coordinates. Our results reject a model without either evolution of galaxy luminosity or evolution of clustering (relative to the stable model) by 4σ at B = 24.5. Similar conclusions were reached from recent CCD data at this magnitude by Neuschaefer (1992). To fit the $\omega(\theta)$ scaling with a no-evolution

N(z) would require a clustering growth rate much greater than would be predicted by any simple gravitational model (e.g. the models of Melott 1992). A model in which N(z) has a no-evolution form and the clustering collapses at the same rate at which the Universe expands is plotted as the dotted line in Fig. 2 — even gravitational clustering evolution as extreme as this has much less effect on the $\omega(\theta)$ amplitudes than the Bruzual model L^* evolution.

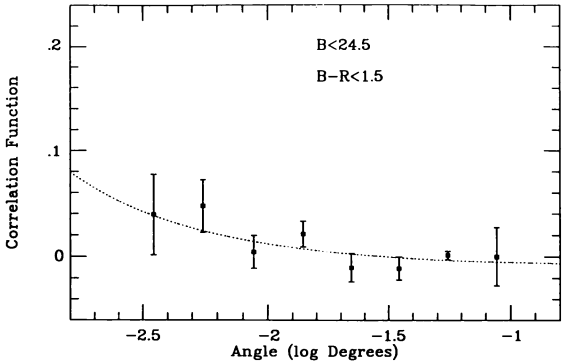
To further investigate the cause of the low $\omega(\theta)$ amplitude at B ~ 24.5, we recalculated $\omega(\theta)$ for our $B_{ccd} \leq 24.5$ galaxies with the data divided into two subsamples — the 701 galaxies with $(B - R)_{ccd} \geq 1.5$ and the 2314 bluer than this. These were found to have significantly different correlation functions (Fig. 3), that of the red galaxies having an amplitude $(24.156 \pm 6.907) \times 10^{-4}\mathrm{deg}^{-0.8}$ and that of the others $(5.016 \pm 3.745) \times 10^{-4}\mathrm{deg}^{-0.8}$. Galaxies within the red subset would only be expected to be seen at $z < 1$ at this magnitude, being E/S0 types with very little star-formation, and their $\omega(\theta)$ is indeed found to be consistent with no evolution. For the bluer galaxies it instead fits the much lower prediction of the Bruzual model. In this model the very blue (flat-spectrum) galaxies which are seen faintward of B $\simeq$ 23 would be at $1 \leq z \leq 3$, and undergoing rapid star-formation.

The colour dependence of $\omega(\theta)$ at B ~ 24.5 would seem to favour the presence of a high-redshift component of blue, actively star-forming galaxies rather than an unexpectedly rapid evolution of the clustering of all galaxies. The very blue colours could also result from starbursts in smaller galaxies at lower redshifts (Neuschaefer 1992), but if such 'blue dwarfs' are dominating the number count excess our results would require them to be less clustered than other galaxies. Hence, if galaxies at B $\simeq$ 24 and fainter are found to have N(z) similar to the no-evolution prediction, more complicated models may be required — such as the inclusion of a very weakly clustered population of dwarf galaxies, with a high number density at $z \sim 0.4$, but which is no longer visible at the present day (Cowie et al. 1991; Babul & Rees 1992).

4. The Redshift Distribution at B ~ 27

Additionally, if the pure luminosity evolution model is correct, it should be possible to see galaxies out to $3 < z < 4$, where they may be first forming, within the limits of the deepest CCD surveys (B $\simeq$ 27.5), whereas this would not be the case without luminosity evolution. Taking our results in conjunction with those of Efstathiou et al. (1991) it appear that the $\omega(\theta)$ amplitude may be approaching a lower limit at B > 24.5. This could be due to the N(z) reaching an upper redshift cut-off at these deep limits, either the epoch of galaxy formation or the result of the Lyman limit becoming redshifted into the B passband at $z \simeq 4$. If the luminosity evolution is sufficiently strong, galaxies may be seen on the faint-end slope of the luminosity function at all redshifts up to the maximum redshift within the magnitude limits of these surveys. On going fainter the form of N(z) would not greatly change and thus the $\omega(\theta)$ scaling would level out. However, at faint limits where the sample becomes dominated by high redshift galaxies, the $\omega(\theta)$ scaling will level out eventually even without a sharp cut-off in N(z), as the reduction in the size of the comoving volume element at high redshifts creates an 'effective cut-off'.

Figure 4 shows median redshift plotted against $\omega(\theta)$ amplitude for our luminosity evolution models computed over a wide range of magnitude limits with both $q_0 = 0.05$ and $q_0 = 0.5$, but with no cut-off in N(z) at high redshift. It can be seen that, although the $\omega(\theta)$ amplitude as a function of the median redshift of the sample continues to decrease at faint magnitudes, the median redshift itself tends to an upper limit. For these models, the median redshift never



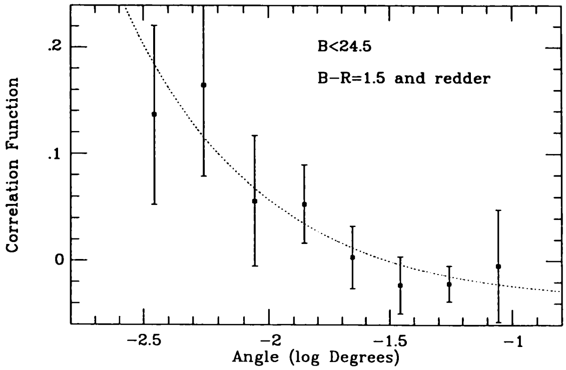


Figure 3. The angular correlation functions of $B_{ccd} \leq 24.5$ galaxies on our 12 CCD frames, divided into blue and red subsamples and shown with field-to-field errors and the fitted $\theta^{-0.8}$ power-laws.

exceeds 2.16 in the $q_0 = 0.5$ geometry, whereas for $q_0 = 0.05$ it can reach ~ 5 as more volume is available at higher redshifts.

The asymptotic minimum value of the $\omega(\theta)$ amplitude will be lower for lower q_0 and for higher upper redshift limits. As shown in Fig. 5, the amplitude at which the $\omega(\theta)$ scaling levels out is in the range we predict for stable clustering and reasonable values of q_0 (i.e. 0 to 0.5) and the cut-off redshift (z_{max} ~ 3 - 4). Figure 5 also shows the $z_{max} = \infty$ models plotted against magnitude limit and it is clear that some levelling out of the $\omega(\theta)$ scaling still occurs without a redshift maximum, and the resulting scaling is still consistent with observations.

The observed levelling out of the $\omega(\theta)$ scaling at $B \geq 24.5$ therefore indicates that the median redshift of galaxies at this depth is exceeding z ~ 1 and/or an upper redshift limit has been reached. Faintward of the magnitude at which this real or effective redshift cut-off is reached, the number counts may continue to increase but with a gradient following the faint-end slope of the luminosity function, which will probably be less steep than the number count slope at brighter

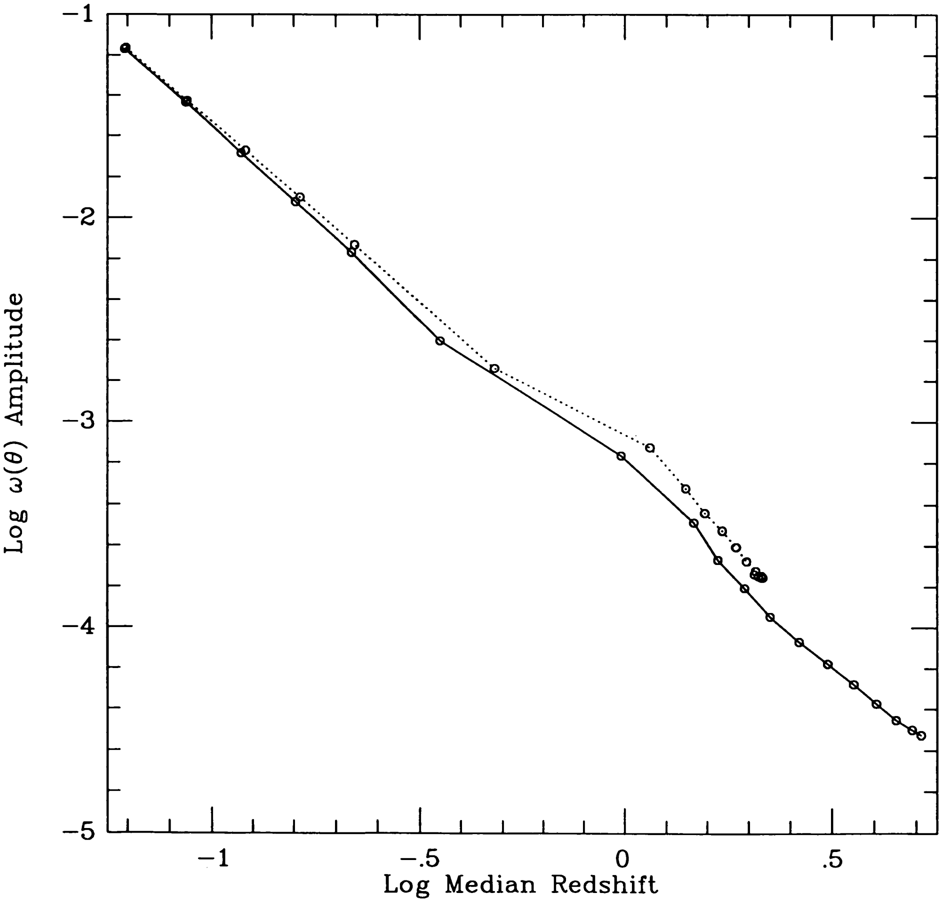


Figure 4. The correlation amplitude plotted against median redshift for our evolving models with $z_{max} = \infty$. The solid line shows the $q_0 = 0.05$ model and the dotted line that computed with $q_0 = 0.5$. The open circles show the corresponding B magnitude limits in one magnitude intervals from $B_{ccd} = 18.0$ (left) to $B_{ccd} = 35.0$ (right).

magnitudes where N(z) is still becoming more extended to higher redshifts. The low ω(θ) amplitude at which this occurs also indicates that (if clustering is assumed stable) the median redshift must be at least $z \sim 1$ for galaxies faintward of B ~ 24.5, and that these galaxies must also be broadly distributed in redshift, to produce a sufficient dilution of the clustering.

Galaxies on our 24hr CCD frame would be expected from their low correlation amplitude and from the Bruzual models to be seen at all redshifts out to at least $z \simeq 3.0$, and Fig. 6 shows our evolving model N(z) at this magnitude limit.

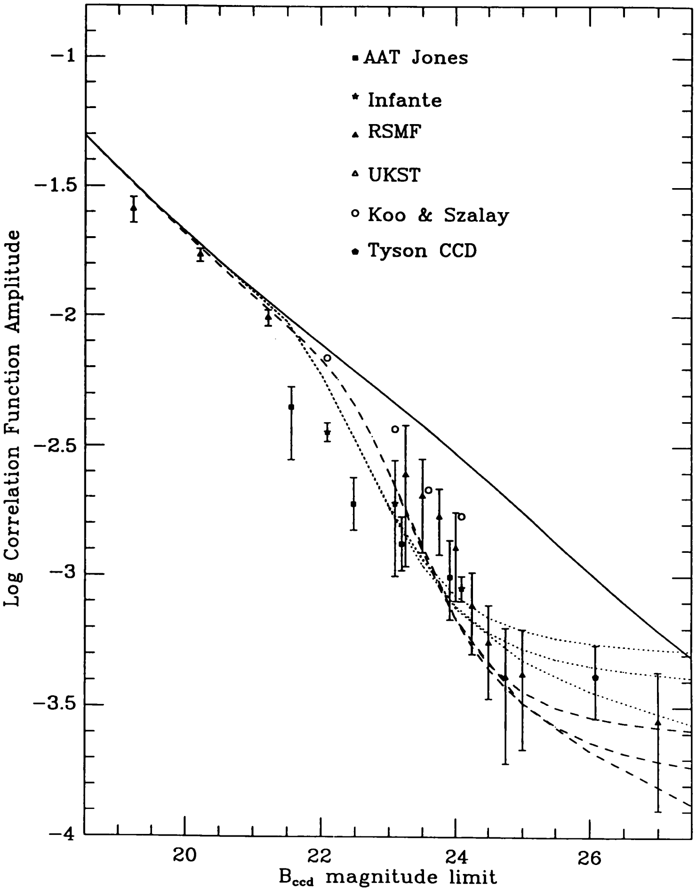


Figure 5. Estimates of the correlation function amplitude obtained from photographic and CCD surveys, compared with the predictions of a non-evolving model (upper curve) as in Fig. 2. The pure luminosity evolution model is computed with $q_0 = 0.05$ (dashed) and $q_0 = 0.5$ (dotted), the curves dividing into three at B > 23 to show the predictions for $z_{max} = 3$ (upper), $z_{max} = 4$ (intermediate) and $z_{max} = \infty$ (lower).

References

Babul, A. and Rees, M.J., 1992. *Mon. Not. R. astron. Soc.*, **255**, 498.

Bruzual, G., 1981. PhD thesis, University of California, Berkeley.

Broadhurst, T.J., Ellis, R.S. and Glazebrook, K., 1992. *Nature*, **355**, 55.

Cowie, L.L., Songaila, A. and Hu, E.M., 1991. *Nature*, **354**, 460.

Efstathiou, G., Bernstein, G., Katz, N., Tyson, J.A. and Guhathakurta, P., 1991. *Astrophys. J.*, **380**, L47.

Infante, L., 1990. PhD thesis, University of Victoria.

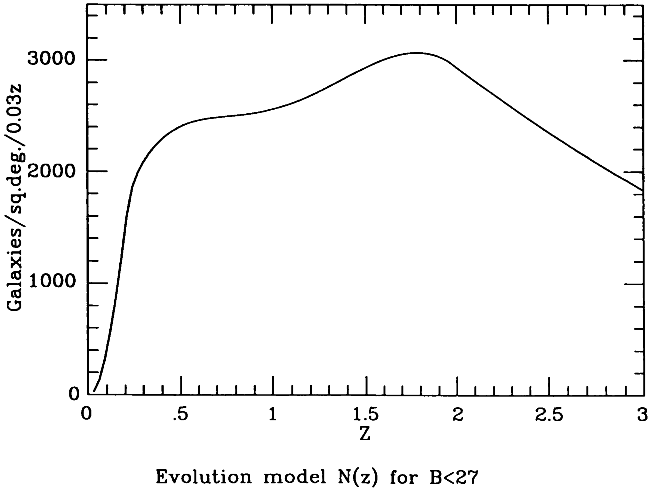


Figure 6. The redshift distribution predicted by our q_0 = 0.05 pure luminosity evolution model for $B_{ccd} \leq 27.0$ galaxies.

Jones, L.R., Shanks, T. and Fong, R., 1987. 'High Redshift and Primeval Galaxies', eds. J. Bergeron, D. Kunth, B. Rocca-Volmerange and J. Tran Thanh Van, Editions Frontières, France, p. 29.

Koo, D.A. and Szalay, A., 1984. *Astrophys. J.*, **282**, 390.

Lilly, S.J., Cowie, L.L. and Gardner, J.P., 1991. *Astrophys. J.*, **369**, 79.

Melott, A.L., 1992. *Astrophys. J.*, **393**, L45.

Metcalfe, N., Shanks, T. and Fong, R., 1991a. *Gemini*, **34**, 12.

Metcalfe, N., Shanks, T., Fong, R. and Jones, L.R., 1991b. *Mon. Not. R. astron. Soc.*, **249**, 498.

Neuschaefer, L.W., 1992. PhD thesis, Arizona State University.

Peebles, P.J.E., 1980. 'The Large-Scale Structure of the Universe', Princeton University Press.

Phillipps, S., Fong, R., Ellis, R.S., Fall, S.M. and MacGillivray, H.T., 1978. *Mon. Not. R. astron. Soc.*, **182**, 673.

Rocca-Volmerange, B. and Guiderdoni, B., 1990. *Mon. Not. R. astron. Soc.*, **247**, 166.

Roche, N., Shanks, T., Metcalfe, N. and Fong, R., 1993. *Mon. Not. R. astron. Soc.*, **263**, 360.

Stevenson, P.R.F., Shanks, T., Fong, R. and MacGillivray, H.T., 1985. *Mon. Not. R. astron. Soc.*, **213**, 953.

Tyson, J.A., 1988. *Astron. J.*, **96**, 1.