THE ASTROPHYSICAL JOURNAL, 399:L35–L38, 1992 November 1

ANGULAR CORRELATION FUNCTION OF FAINT GALAXIES

C. J. PRITCHET[1,3] AND L. INFANTE[2,3]

Received 1992 July 14; accepted 1992 August 14

ABSTRACT

The angular correlation function has been computed for a two-color survey of faint galaxies ($J < 24$, $F < 23$) covering a ~ 2.4 deg^2 area near the North Galactic Pole. Faint galaxies are found to belong to a population that is more weakly clustered than luminous nearby galaxies, by a factor $\gtrsim 2$ at $J = 22$ and $\gtrsim 4$ at $J = 24$. Objects selected in the F (red) band are closer to model predictions than those observed in the J band. These observations are interpreted in terms of models in which (weakly clustered) bursting dwarf galaxies comprise the bulk of the number counts at faint magnitudes.

Subject headings: cosmology: observations — galaxies: clustering — galaxies: evolution

1. INTRODUCTION

A number of groups have drawn attention to the large numbers of blue galaxies that dominate source counts at faint magnitudes (e.g., Tyson 1988; Lilly, Cowie, & Gardner 1991 and references therein). Number counts of faint galaxies exceed the predictions of simple no-evolution models by a factor of ~ 2 at the relatively bright magnitude of $b_J = 21$, rising to as much as a factor of 5 at $b_J = 24$ (Maddox et al. 1990b). Paradoxically, most evolutionary models that match the observed counts predict many more high-redshift galaxies than actually observed; the best-fit redshift distribution for faint galaxies is close to a no-evolution model down to at least $b_J = 24$ (Broadhurst, Ellis, & Shanks 1988, hereafter BES88; Colless et al. 1990; Lilly et al. 1991; Cowie, Songaila, & Hu 1991; Lilly 1992; Colless et al. 1992). As Lilly et al. (1991) have emphasized, this result logically suggests an increase in ϕ^*, the (comoving) number density of L^* galaxies, at moderate redshifts ($z \gtrsim 0.2$). One explanation for this effect is bursts of star formation in (relatively numerous) dwarf galaxies (BES88; Babul & Rees 1992), possibly driven by mergers (Carlberg & Charlot 1992; Broadhurst, Ellis, & Glazebrook 1992). These bursting dwarfs may belong to a population that has faded significantly, so that it is not represented in catalogs of nearby galaxies (Babul & Rees 1992; Cowie et al. 1991).

In this *Letter* we investigate the clustering properties of faint galaxies. We find that faint galaxies are significantly weaker in their two-point angular correlation function than would be predicted from simple models. This conclusion is in agreement with a recent result by Efstathiou et al. (1991). Our work differs from that of Efstathiou et al. because it samples galaxies at brighter magnitudes, where the redshift distribution (a key ingredient in the analysis) is better known.

2. OBSERVATIONS AND REDUCTIONS

The data used in this *Letter* are derived from the Canada-France-Hawaii-Telescope (CFHT) North Galactic Pole Survey (Infante & Pritchet 1992, hereafter Paper I). Plates were acquired in the Kron (1980) J and F system for five fields arranged in a "checkerboard" configuration (total area 2.4 deg^2); the seeing for all observations was $\lesssim 1''$ FWHM. The plates were scanned on the Cambridge APM, and total magnitudes, image classification parameters, and astrometric positions were derived. Photometric zero points were obtained using CCD observations of a number of fields on each plate. A number of external checks verify that the magnitude scale is linear, and that zero-point variations appear to be less than ± 0.05 mag over the fields. The resultant catalog of approximately 40,000 galaxies is estimated to be more than 90% complete to $J = 24$ and $F = 23$. The reader is referred to Paper I for further details.

The angular correlation function $\omega(\theta)$ was computed using a method that is described more fully in Infante (1990, 1992; see also Infante & Pritchet 1992, hereafter Paper III). An artificial catalog of randomly distributed objects was created, and areas contaminated by plate defects, bright stars, vignetted areas, etc., were masked from both the artificial catalog and the real catalog. The estimator used was

$$1 + \omega(\theta) = \frac{N_{gg} N_r}{B N_{gr}(N_g - 1)} - \omega_{rg}(\theta) , \qquad (1)$$

where N_{gg} is the number of galaxy pairs in a given range of separations, N_{gr} is the number of random pairs using galaxies as centers, N_g is the number of galaxies, and N_r is the number of random objects. B is the "integral constraint" correction factor (e.g., Peebles 1980; Koo & Szalay 1984), computed in this work using an iterative technique that ensures consistency between B and $\omega(\theta)$. The quantity ω_{rg} is a correction for sample boundary effects (Hewett 1982) that is quite small in this work. Our algorithm has been checked with artificially generated catalogs.

3. RESULTS

The computed correlation functions are shown in Figure 1 for the J band. We have fitted a power law $\omega(\theta) = A_\omega \theta^{-\delta}$ to the data, with a steeper power-law cutoff at large θ. Enforcing a "canonical" slope $\delta = 0.8$ (e.g., Davis & Peebles 1983; but see Maddox et al. 1990a) yields amplitudes $A_\omega^{\delta=0.8}$ that are tabulated in Table 1 for both the J and F bands. Further details on the fitting procedure may be found in Paper III.

The scaling of the correlation amplitudes $A_\omega^{\delta=0.8}$ with limiting magnitude is shown in Figures 2 and 3 for the J and F

---

[1] Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC, Canada V8W 3P6.

[2] Grupo de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Casilla 104, Santiago 22, Chile.

[3] Visiting Astronomer, Canada-France-Hawaii Telescope, which is operated by the National Research Council of Canada, le Centre National de Recherche Scientifique, and the University of Hawaii.

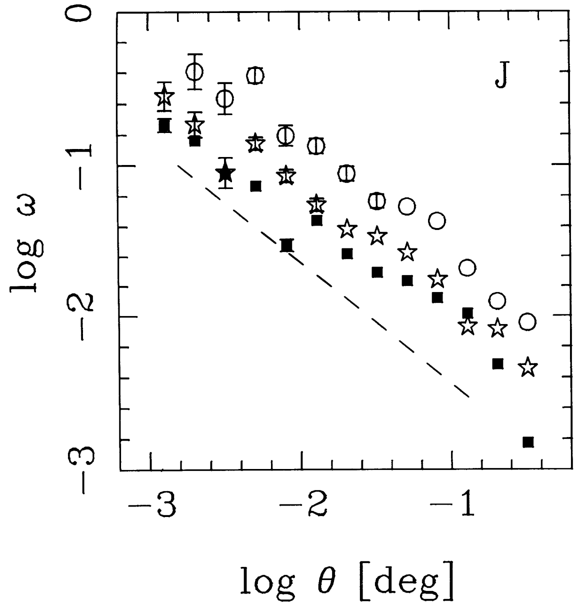

FIG. 1.—Angular correlation function for different magnitude ranges in the J band. *Circles:* 20–22; *stars:* 20–23; *filled squares:* 20–24. Error bars are plotted if they exceed the size of the symbols. The dashed line has slope −0.8. It can be seen that fainter galaxies possess weaker correlation amplitudes, as expected.

bands. These amplitudes drop off in a monotonic fashion with fainter magnitude, as expected for samples with increasing effective depth. A detailed comparison of these amplitudes with those of other groups will be presented in Paper III. Here we note that our J amplitudes agree reasonable well with the data of Jones, Shanks, & Fong (1987) and Neuschaefer, Windhorst, & Dressler (1992), and lie smoothly between the data of Maddox et al. (1990a) at $J \leq 20.5$ and Efstathiou et al. (1991) at $J \leq 26$.

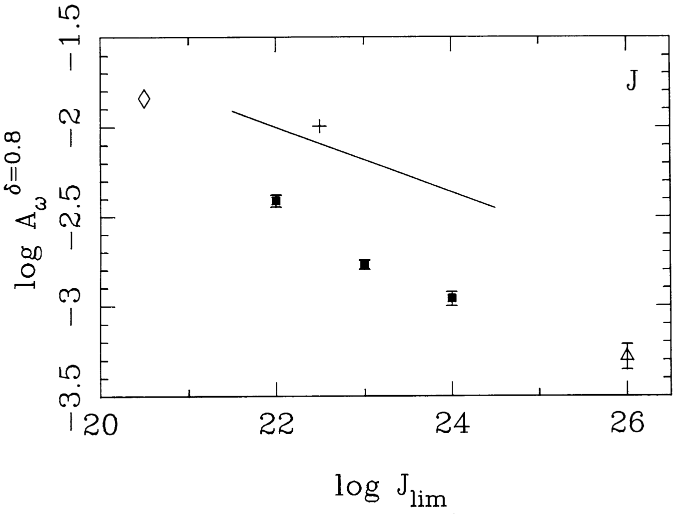

FIG. 2.—Correlation amplitudes as a function of limiting J-magnitude, assuming a power-law slope of $\delta = 0.8$ for $\omega(\theta)$. *Squares:* this work; *diamond:* Maddox et al. (1990a); *triangle:* Efstathiou et al. (1991). The position of the Maddox et al. data point is an estimate, because $\delta = 0.66$ clearly provides a better fit to their data than $\delta = 0.8$. The solid line is the no-evolution model described in the text, and the plus sign is a model in which the observed redshift distribution of Colless et al. (1990) and Broadhurst et al. (1988) is used.

TABLE 1

CORRELATION FUNCTION AMPLITUDES

Magnitude Range	$A_\omega^{\delta=0.8}$
$20 \leq J \leq 22$	0.0039 ± 0.0003
$20 \leq J \leq 23$	0.0017 ± 0.0001
$20 \leq J \leq 24$	0.0011 ± 0.0001
$19 \leq F \leq 21$	0.0050 ± 0.0003
$19 \leq F \leq 22$	0.0029 ± 0.0003
$19 \leq F \leq 23$	0.0019 ± 0.0002

4. DISCUSSION

The calculation of $\omega(\theta)$ from ξ depends on the distribution of overlapping structures along the line of sight—that is, on dN/dz. To see this, let us write the two-point spatial correlation function as

$$\xi(r, z) = (r_0/r)^\gamma (1 + z)^{-(3+\epsilon)} , \tag{2}$$

where $r_0 = 5.5\ h^{-1}$ Mpc, $\gamma = 1.8$ (e.g., Davis & Peebles 1983), and ϵ describes clustering evolution with redshift. The parameter ϵ should lie between 0 (dynamically bound, stable clustering fixed in proper coordinates) and −1.2 (clustering fixed in comoving coordinates). Then $\omega(\theta) = A_\omega \theta^{(1-\gamma)}$, and A_ω is given by

$$A_\omega = C r_0^{-\gamma} \frac{\int_0^\infty g(z)(dN/dz)^2\, dz}{[\int_0^\infty (dN/dz) dz]^2} \tag{3}$$

(e.g., Efstathiou et al. 1991; see also Peebles 1980; Phillips et al. 1978). C is a constant involving purely numerical factors, and the function $g(z)$ depends only on ϵ, γ, and cosmology. The H_0 dependence of $g(z)$ is exactly canceled by that in the measured value of r_0. The strong dependence of A_ω on dN/dz is clear in this equation. Note in particular that *there is no dependence on galaxy evolution in equation (3), except in the calculation of the redshift distribution dN/dz.*

It has already been noted in the Introduction that dN/dz for galaxies with $J \lesssim 24$ (and, presumably, $F \lesssim 23$) does not differ significantly from the no-evolution form. We have therefore computed the expected correlation amplitudes using no-evolution redshift distributions. (The fact that such models fail

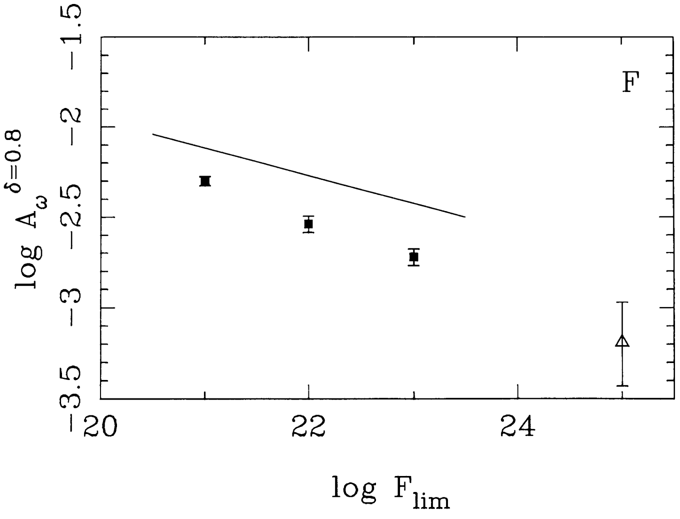

FIG. 3.—Same as for Fig. 2, but for the F band

to explain the number counts is irrelevant for the present purpose.) The no-evolution model chosen is that of Metcalfe et al. (1992); the predicted A_ω values have been computed assuming $\gamma = 1.8$, $\epsilon = 0$, $\Omega = 0.2$, and $r_0 = 5.5\ h^{-1}$ Mpc. The results are shown by the solid lines in Figures 2 and 3. Similar results are obtained using the model of BES88. Our "no-evolution" correlation amplitudes agree reasonably well with those tabulated by Koo & Szalay (1984).

The effect of raising Ω to 1 is to increase the predicted log A_ω by 0.02–0.06 (depending on passband and magnitude); adopting $\epsilon = -1.2$ raises log A_ω by ~ 0.1. Also shown in Figure 2 is a correlation amplitude for $20 \leq J \leq 22.5$ computed using the actual *observed* dN/dz for this magnitude range (obtained by combining the z surveys of Broadhurst et al. 1992 and Colless et al. 1990). This is in acceptable agreement with the models computed assuming a no-evolution form for dN/dz.

From Figures 2 and 3 we conclude that *the bulk of the galaxy population observed at faint magnitudes* ($J \gtrsim 22$, $F \gtrsim 21$) *is weakly clustered compared to nearby galaxies*, by about a factor of 4–5 at $J \approx 24$, and ~ 2 at $F \approx 23$. Equivalently, the correlation length r_0 of faint galaxies is inferred to be a factor ~ 2 smaller than for local galaxies. This conclusion would be made stronger if $\Omega > 0.2$ or if $\epsilon < 0$. Formally, $\epsilon \approx 4$ would be required to explain the observations—a result that we view as unphysical.

The above conclusion is similar to that of Efstathiou et al. (1991) for galaxies at much fainter magnitudes ($J \lesssim 26$). We believe our conclusion to be more secure, because it makes use of galaxies at a magnitude level for which there exist *observed* redshift distributions, and it is based on galaxy correlations with a greater statistical significance. Furthermore, the interpretation of our observations is more straightforward, because it involves galaxies at relatively low mean redshift (see below).

Could the observations be better explained using a different value of γ or δ? Maddox et al. (1990a) have shown that $\delta = 0.66$ provides the best fit to the observed clustering properties of $\sim 2 \times 10^6$ galaxies in the APM survey (4300 deg^2, $b_J < 20.5$). In fact, $\delta \simeq 0.6$–0.7 also provides a reasonable fit to the data in Figure 1, and the fitted correlation amplitudes assuming $\delta = 0.66$ are about 1.5–2 times larger than for $\delta = 0.8$. However the predicted A_ω values *also* rise, by about 1.4 times, so that the net discrepancy is still about a factor of 3 in clustering amplitude observations and models (for $J < 24$).

A number of groups (e.g., Maddox et al. 1990b; Lilly et al. 1991) have noted that a factor of ~ 3–5 more galaxies are observed at $J = 24$ than are predicted by models that are consistent with the observed redshift distribution. It therefore seems natural to assume that the low observed clustering amplitude at $J \lesssim 24$ can be attributed to weak clustering of the *excess* population itself. Formally one can write the expected clustering amplitude of two uncorrelated populations with different clustering properties as $A = f_1^2 A_1 + f_2^2 A_2$. If $f_{\rm excess} \simeq 0.7$ and $A_\omega({\rm obs}) \simeq 0.25 A_\omega({\rm model})$, then the true clustering amplitude of the excess component must be ~ 0.3 that of luminous galaxies nearby (or less if there exists some cross-correlation between the two samples). The fact that the deficit in clustering amplitude (relative to model predictions) increases toward fainter magnitudes is consistent with the fact that the "excess" population is a greater fraction of the total counts at $J = 24$ than at $J = 22$.

How can the low clustering amplitude (*and* excess numbers) of faint galaxies be understood? Because of the relatively low mean redshift of galaxies at $J \lesssim 24$ ($\langle z \rangle \approx 0.4$—e.g., Lilly 1992, Cowie et al. 1991), one can probably rule out explanations for the observed clustering effect based on nonstandard cosmologies or clustering evolution (cf. Efstathiou et al. 1991). A possible explanation of the "$N(m) - dN/dz$" paradox is that dwarflike galaxies that are undergoing bursts of star formation dominate the counts (BES88; Babul & Rees 1992). If such galaxies (observed as dwarfs today) were clustered more weakly than luminous galaxies, then our low observed clustering amplitude might be naturally explained. Moreover, the fact that galaxies selected in the F band possess clustering amplitudes closer to no-evolution model predictions would be explained naturally in such a scenario, because the fraction of "excess" (unclustered, bursting) galaxies would be smaller in red light.

A number of groups have searched for a difference in the clustering properties of high and low L galaxies, with mixed results. Several recent studies (e.g., Salzer, Hanson, & Gavazzi 1990; Giovanelli & Haynes 1988; Hollósi & Efstathiou 1988) have claimed that low L galaxies have a lower clustering amplitude than high L galaxies. However, other groups (e.g., Eder et al. 1989; Thuan, Gott, & Schneider 1987; Bothun et al. 1986) have found no such effect. Further observations are clearly required to resolve this ambiguity, but it should be noted that the observed ratio $\xi_{\rm L*}/\xi_{\rm dwarf}$ probably does not exceed a factor of ~ 2 (cf. Salzer et al. 1990; Thuan et al. 1991) and hence may be too small to explain our observations.

Babul & Rees (1992) have proposed that the first burst of star formation in low-mass dwarfs is delayed until $z \lesssim 1$ by photoionization and heating by the UV background. The subsequent evolution of such galaxies depends on environment. In low-density environments, a supernova-driven wind will quench star formation, and the initial burst of star formation will fade to obscurity. In high-density environments, on the other hand, the wind may be suppressed by a high-pressure intergalactic medium, so that further generations of star formation can take place. This theory naturally predicts that surviving visible dwarfs should be strongly clustered at the present epoch, as observed (e.g., Binggeli, Tarenghi, & Sandage 1990; Thuan et al. 1991), but predicts that the parent population from which these objects were drawn possessed lower clustering amplitude, and has since faded below the threshold of catalogs of nearby galaxies. In this picture it is therefore possible to produce *apparent* evolution both in the clustering properties of dwarf galaxies and in the number counts. It is also worth noting that, according to this scenario, (gas-poor) dE galaxies should be more clustered than (gas-rich) dIrr galaxies, as is observed (Binggeli et al. 1990).

We note that the low clustering amplitude that is observed for faint galaxies would seem to argue against models in which starbursts are triggered by mergers and interactions (e.g., Carlberg & Charlot 1992; Broadhurst et al. 1992). However, the merger rate depends not only on $\xi(r)$ but also on galaxy density. In "bursting dwarf" models, the present-day analogues of the $\sim$L* galaxies that dominate the faint counts are dwarfs, which have a higher number density than L* galaxies; in addition there is the obvious $(1 + z)^3$ dependence of proper density. Furthermore, there is indirect empirical evidence from a variety of sources that the merger rate in the past *was* in fact higher than at the present epoch (e.g., Carlberg 1992 and references therein). We conclude that, in spite of low clustering amplitude, it is not possible to rule out a merger origin for the bursts of star formation that have been proposed in faint galaxies.

Finally, it is interesting to note that the correlation function of galaxies selected by *IRAS* 60 μm flux displays both a shallower slope and shorter correlation length r_0 than for normal galaxies (Saunders, Rowan-Robinson, & Lawrence 1992; Strauss et al. 1992). The fact that *IRAS*-selected galaxies possess high star formation rates, a property that has also been invoked to explain the excess counts of faint galaxies (e.g., BES88, Babul & Rees 1992) may suggest that there is a link between these two classes of objects.

5. CONCLUSIONS

We have determined the angular correlation function $\omega(\theta)$ for faint ($22 \lesssim J \lesssim 24$, $21 \lesssim F \lesssim 23$) galaxies. Our results indicate that faint galaxies are clustered more weakly (by a factor of 3–5) at these magnitudes than nearby luminous galaxies. This result is based on observed redshift distributions from a number of sources and is not strongly dependent on cosmology or on assumptions regarding the redshift evolution of clustering. We conclude, as did Efstathiou et al. (1991), that the excess population of galaxies that appears in the faint number counts is weakly clustered. This result is consistent with a model in which bursting dwarf galaxies explain the excess number counts at faint magnitudes (e.g., BES88; Babul & Rees 1992), provided that dwarf galaxies at moderate redshift are clustered more weakly than nearby luminous galaxies.

We are grateful to Ray Carlberg and David Hartwick for helpful discussions. This work was supported by the Natural Sciences and Engineering Council of Canada, and Proyecto FONDECYT 635/91.

REFERENCES

Babul, A., & Rees, M. J. 1992, MNRAS, 255, 346
Binggeli, B., Tarenghi, M., & Sandage, A. 1990, A&A, 228, 42
Bothun, G. D., Beers, T. C., Mould, J. R., & Huchra, J. P. 1986, ApJ, 308, 510
Broadhurst, T. J., Ellis, R. S., & Glazebrook, K. 1992, Nature, 355, 55
Broadhurst, T. J., Ellis, R. S., & Shanks, T. 1988, MNRAS, 235, 827 (BES88)
Carlberg, R. G. 1992, in Cosmology and Large-Scale Structures in the Universe, ed. R. de Carvalho (ASP Conf. Series), in press
Carlberg, R. G., & Charlot, S. 1992, ApJ, 397, 5
Colless, M., Ellis, R. S., Broadhurst, T. J., Taylor, K., & Peterson, B. A. 1992, MNRAS, in press
Colless, M., Ellis, R. S., Taylor, K., & Hook, R. N. 1990, MNRAS, 244, 408
Cowie, L. L., Songaila, A., & Hu, E. M. 1991, Nature, 354, 460
Davis, M., & Peebles, P. J. E. 1983, ApJ, 267, 465
Eder, J. A., Schombert, J. M., Dekel, A., & Oemler, A. 1989, ApJ, 340, 29
Efstathiou, G., Bernstein, G., Katz, N., Tyson, J. A., & Guhathakurta, P. 1991, ApJ, 380, L47
Giovanelli, R., & Haynes, M. P. 1988, in Towards Understanding Galaxies at High Redshift, ed. R. G. Kron & A. Renzini (Dordrecht: Kluwer), 133
Hewett, P. C. 1982, MNRAS, 201, 867
Hollósi, J., & Efstathiou, G. 1988, in Large-Scale Structures in the Universe: Observational and Analaytical Methods, ed. W. C. Seitter, H. W. Duerbeck, & M. Tacke (Berlin: Springer), 106
Infante, L. 1990, Ph.D. thesis, Univ. Victoria
———. 1992, A&A, submitted
Infante, L., & Pritchet, C. J. 1992, ApJS, in press (Paper I)
Infante, L., & Pritchet, C. J. 1992, in preparation (Paper III)
Jones, L. R., Shanks, T., & Fong, R. 1987, in High Redshift and Primeval Galaxies, ed. J. Bergeron, D. Kunth, B. Rocca-Volmerange, & J. Tran Thanh Van (Gif-sur-Yvette: Éditions Frontières), 29
Koo, D. C., & Szalay, A. S. 1984, ApJ, 282, 390
Kron, R. G. 1980, ApJS, 43, 305
Lilly, S. J. 1992, ApJ, submitted
Lilly, S. J., Cowie, L. L., & Gardner, J. P. 1991, ApJ, 369, 79
Maddox, S. J., Efstathiou, G., Sutherland, W. J., & Loveday, J. 1990a, MNRAS, 242, 43P
Maddox, S. J., Sutherland, W. J., Efstathiou, G., Loveday, J., & Peterson, B. A. 1990b, MNRAS, 247, 1P
Metcalfe, N., Shanks, T., Fong, R., & Jones, L. R. 1991, MNRAS, 249, 298
Neuschaefer, L. W., Windhorst, R. A., & Dressler, A. 1992, ApJ, 382, 32
Peebles, P. J. E. 1980, The Large-Scale Structure of the Universe (Princeton: Princeton Univ. Press)
Phillipps, S., Fong, R., Ellis, R. S., Fall, S. M., & MacGillivray, H. T. 1978, MNRAS, 182, 673
Salzer, J. J., Hanson, M. M., & Gavazzi, G. 1990, ApJ, 353, 39
Saunders, W., Rowan-Robinson, M., & Lawrence, A. 1992, MNRAS, in press
Strauss, M. A., Davis, M., Yahil, A., & Huchra, J. P. 1992, ApJ, 385, 421
Thuan, T. X., Alimi, J.-M., Gott, J. R., & Schneider, S. E. 1991, ApJ, 370, 25
Thuan, T. X., Gott, J. R., & Schneider, S. E. 1987, ApJ, 315, L93
Tyson, J. A. 1988, AJ, 96, 1