QUASAR CLUSTERING

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## 1. THE SKY DISTRIBUTION OF QUASARS

If quasars are distributed cosmologically according to their redshifts, then it is expected that their distribution on the sky will be very close to random, because it is in that case an average over an enormous range in distance. Most studies find no significant clustering. It has recently been suggested, however, that there may be a highly significant excess of close pairs of quasars with different redshifts[1], although this has been disputed[2]. The new ROE/ESO quasar survey[3] provides a very large and deep sample over a connected area of sky, ideal for a more sensitive search for clustering. The result is shown in fig. 1. The observed distributions appear to be random, on all scales from less than an arcmin to tens of degrees.

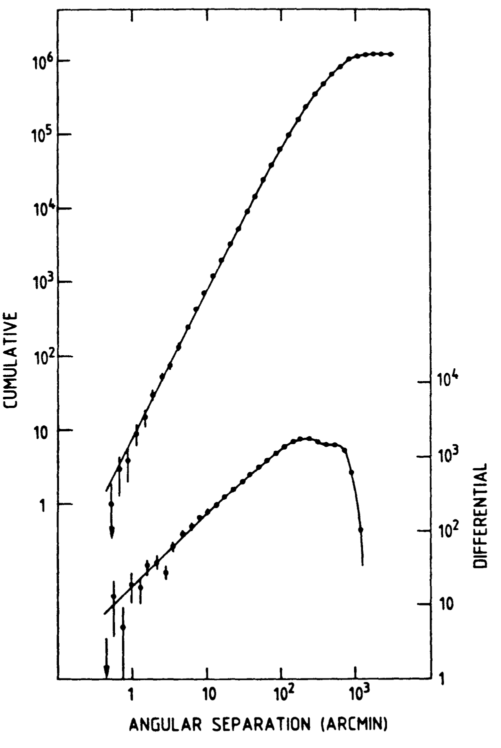


Figure 1. - Cumulative and differential numbers of quasar pairs from the ROE/ESO survey, as a function of angular separation. The solid lines represent Monte Carlo simulations for a purely random distribution.



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## 2. QUASAR-GALAXY CLUSTERING

Quasars at low redshifts are located preferentially in compact groups or clusters of galaxies[4-9], with relatively small ($\sim 60\ h^{-1}$ kpc) and dense cores. Typical quasar-galaxy redshift differences are $\sim 300$-$400$ km $s^{-1}$. The quasar-galaxy correlation function is stronger than the galaxy-galaxy correlation function, and strongest in the case of radio-loud quasars[6]. A large fraction of quasars have very close distorted or compact companions[5,8,9]. These facts strongly suggest that interactions are often involved in activating and fuelling quasars.

The association of quasars with galaxies appears to be even stronger at higher redshifts[10,11]. At the highest redshifts the evidence is largely indirect: narrow absorption lines near the emission redshift[12-14], highly distorted radio structures[15], and a possible quasar-galaxy pair at $z = 3.2$[16]. Quasars may therefore be located in groups or clusters of galaxies at all redshifts, and it has been suggested that the clustering environment may be richest at the highest redshifts[17].

## 3. QUASAR-QUASAR CLUSTERING

Quasar clustering has been difficult to detect and measure reliably, because of the very low space density of these objects, and complications due to selection effects and "contamination" from gravitational lensing which can in principle produce image splittings of arcminutes.[18,19] The problem of distinguishing between gravitational lenses and physical pairs has been discussed by several authors[20-23], and cannot easily be solved in individual cases. However, the contamination due to lenses is not likely to be statistically important in large-scale clustering analyses.

Two approaches have been taken in studies of quasar clustering. Homogeneous samples have been examined for evidence of physical clustering, but these have been generally too small, too shallow, or both. Larger and deeper samples are now being produced, but so far the results are contradictory: Clowes et al.[24] find no clustering at high redshifts in a large AQD sample, and Crampton et al. [25] find no clustering amongst quasars from a grens survey, but Boyle et al.[26] find tentative evidence for strong clustering in their UVX sample.

Alternatively, large quasar catalogues have been used to search for clustering - these provide large numbers of quasars, but they are heterogeneous, and a special technique has had to be used to minimize selection effects[27]. This approach gave early evidence of possible quasar clustering[27], and the same technique now gives preliminary indications that quasar clustering on large scales may increase strongly with decreasing redshift[28,29]. Efforts are underway to refine the clustering analysis of large catalogues, and to enlarge the homogeneous samples, and it is hoped that a more consistent picture of quasar clustering will soon emerge.

A knowledge of quasar clustering and its evolution may provide useful constraints on cosmological models. At high redshifts, it would provide information on whatever large-scale structure existed at early epochs, and possibly on the mass distribution of the intervening medium through considerations of gravitational lensing. And a study of the evolution of quasar clustering towards lower redshifts may yield information on the way in which structure evolved on different scales.

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## DISCUSSION

ARP: It appears your maximum clustering affect comes for quasars of redshift z ~ 1. I would like to remind you that at the Liege Conference in 1983 I showed that the five densest groups of quasars known all had redshifts near z ~ 1. But, and this point needs to be faced, these groups of quasars contained redshifts which had a range of at least several tenths from the mean redshift of the group.

SHAVER: A preliminary examination of the quasar pairs that comprise the possible excess at low redshifts does not reveal any obvious bias or preferred redshift.

BOYLE: Have you tried to model the z dependence of the QSO-QSO correlation length with typical models for the evolution of galaxy clustering with redshift?

SHAVER: No, we would first like to improve the data set to obtain a consistent picture of QSO clustering and its evolution, before making any comparisons with models.

HARTWICK: As reported by Dr. Crampton we found no evidence for widespread clustering in the CFHT survey as a whole. In addition, when the sample was divided into two groups at the median redshift of z ~ 1.6 no statistically significant evidence for clustering was found in either the low or high redshift subsamples.

ULMER: QSO's are supposed to be in clusters. Why don't we see QSO clustering as clusters are correlated?

SHAVER: The analyses of QSO catalogues suggest that QSO clustering may approach that of clusters of galaxies at the lowest redshifts, although this remains to be confirmed using large homogeneous samples.

BAHCALL: You have described 2 trends that appear to go in opposite directions. If QSOs are more strongly associated with richer galaxy clusters at higher redshifts, I would have expected the QSO correlation function to be stronger at these higher z's, resembling more the cluster-cluster correlation function, while at smaller z's the correlation would be weaker. The results of the QSO correlation, however, are exactly opposite to this trend. Can you comment on these trends?

SHAVER: The QSO-galaxy correlation is on small scales (< 1 Mpc), whereas the QSO-QSO clustering may reflect structure on much larger scales. Therefore, if these trends are correct, they may indicate that structure on the largest scales was the last to form.

YEE: In regard to Neta Bahcall's question, I would like to point out that the increased quasar-galaxy co-variance amplitude at higher redshift has only been found for radio-loud quasars so far. Since most of the quasar-quasar clustering tests use optical quasar samples, the fact that no strong clustering of quasars has been found at high z is not necessarily contradictory.

TURNER: Even though the relative roles of physical clustering and gravitational lensing in producing close ($\Delta\theta \lesssim 10''$) high redshift quasar pairs will be difficult to determine on a case by case basis, there should be a straightforward statistical test. If physical clustering is important, many of the pairs should have a small but easily measurable redshift difference between the two components.

SHAVER: Yes, but the required number of such pairs may be large, in view of the uncertainty in redshifts measured from the broad emission lines.

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