QUASARS AND SUPERCLUSTERS

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The topic of quasars and superclusters is only a few years old. Although the first pairs of quasars with small angular separations on the sky were found ten years ago (Stockton 1972, Wampler et al. 1973), the pair members had very different redshifts. The surface density of samples with available redshifts at that time was far too low for cases of quasars with both small angular separations and small redshift differences to turn up. Setti and Woltjer (1977) pointed out that if quasars occur in the nuclei of giant elliptical galaxies, then clustering should be apparent at 20th magnitude and fainter. In 1979 Walsh, Carswell and Weymann found a very close pair with identical redshifts; that, of course, was the first discovery of a gravitational lens. Also in 1979 Arp, Sulentic, and di Tullio showed that some of the quasars near NGC 3389 had similar redshifts, although at that time they did not discuss the hypothesis of the quasars being associated with superclusters. Subsequently Burbidge et al. (1980) confirmed that a compact (5 minutes of arc) group of 3 quasars found by Hoag on a 4m grating prism plate of the M82 field had very similar redshifts. Indeed, the group had the dimensions of a galaxy cluster, not a supercluster. Oort, Arp, and de Ruiter (1981) then specifically called attention to the fact that enough pairs of quasars with similar redshifts were known to suggest that quasar associations on the scale of galaxy superclusters do exist.

However, independent analyses of the Cerro Tololo surveys for large redshift quasars (Osmer and Smith 1980, Hoag and Smith 1977, Osmer 1980) did not find evidence for clustering of the quasar population as a whole. Osmer (1981) noted that many groups and pairs with similar redshifts could be found that had separations of supercluster size but demonstrated that the eye was a poor judge of their statistical significance. After he allowed for the various selection effects in the catalogs and applied binning analysis, the nearest neighbor test, and the correlation function method to the data, he concluded that there was no evidence for a departure from randomness in the quasar distribution. Webster (1982), in a separate study of the Curtis Schmidt quasars, came to the same conclusion by using power spectrum analysis, with the exception that he showed that one low redshift ($z \sim 0.37$) group is a significant enhancement.

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The present state of the topic is that there is agreement that quasars with separations comparable to or less than the size of superclusters are known, but there is no agreement that quasars in general tend to cluster. It is my opinion that the available data are not adequate to demonstrate the latter point, although surveys currently under way are likely to provide much improved limits on the clustering of quasars.

The potential importance of any connection between quasars and superclusters is clear. At large redshifts ($z \gtrsim 1$), quasars are still the only available indicators of the large scale structure of the universe. Now that large samples with high surface density are becoming available, it is possibly to study the quasar distribution on much smaller scales than could be done previously. For example, in the Hoag-Smith (1977) 4m survey, the average nearest neighbor distance at $z \sim 2$ is 64 h^{-1} ($h = H_o/100$) Mpc (Osmer 1981) in present epoch coordinates or 21 h^{-1} Mpc at a time corresponding to $z = 2$. The expectations of finding significant structures on such scales has increased recently as a result of work on a region of low galaxy density (Kirshner et al. 1981) which appears to be surrounded by a region of galaxy overdensity (Bahcall and Soneira 1982a). Therefore the strength of galaxy clustering on supercluster scales of 50 h^{-1} Mpc appears to be much higher than previously thought.

The theoretical aspects of clustering and their relation to cosmology are an extensive field in themselves, which is amply discussed elsewhere in this symposium. Here I believe it is important to concentrate on the observational side of the problem. A sound understanding of the data base and its limitations must be attained before theoretical conclusions about the observations can be drawn. The recent literature already contains several articles having entirely opposite conclusions about the significance of clustering just in the Cerro Tololo samples (cf. Arp 1980, Sulentic 1981 in addition to the references mentioned already).

In my opinion the most dangerous pitfall in analyzing data for clustering is to assume uniformity in the selection process. While the assumption is a natural one to make and allows simple analytic estimates of expected probabilities, it is not sufficiently appreciated that <u>any deviation from uniformity in the selection process will produce apparent clustering</u> in analyses that assume uniformity. A discussion of this problem is given by Osmer (1981). For example, large scale trends in the data can produce apparent clustering. Such a trend in right ascension in the Curtis Schmidt survey has much to do with the effects noted by Arp (1980) and Sulentic (1981).

The steepness of the apparent quasar luminosity function is another difficulty in achieving adequate uniformity in surveys. If the number of quasars increases by a factor of 8 per magnitude, then a 0.2 mag variation in limiting sensitivity in a survey will lead to a 50% difference in the expected number of objects. Such a variation could occur between different observations or be caused in part by variable interstellar absorption. Clearly such effects must be taken into account in any analysis of the data.

A related problem is the uneven sampling in redshift that occurs in any magnitude-limited survey. At larger redshifts only the most luminous objects are detected, and their space density is lower than that of less luminous objects. Of course, any variation in the overall space density with redshift must be considered as well. Finally, all observational techniques for finding quasars have redshift biases of their own that have to be considered.

Specifically, the main difference between the work of Osmer (1981) and Webster (1982), who concluded that quasars on the whole do not show evidence for clustering, and that of Oort et al. (1981) as well as Sulentic (1981), who claimed evidence for associations of quasars with each other or with bright galaxies, is that the latter papers based their expected values on the assumption of uniform sampling while the former two made allowance for the non-uniformities in the data. Again, there is general agreement that some close pairs and groups of quasars with similar redshifts exist and that they occur on the scales of superclusters or smaller, but there is definitely not agreement that quasars in general show evidence for clustering.

It is clearly important to continue work on this purely observational side of the problem. New surveys in previously unstudied areas of the sky are needed for at least two reasons. First, many of the surveys done to date were not set up to study clustering, and often were centered on already known quasars or other previously studied objects. Thus the results are not statistically independent from previous ones. Second, Wills' (1978) precept continues to be very timely -- the best check of an unusual result or configuration found after the fact in a given survey is to look again for the same thing in another field. Finding something else from what was sought in the new survey does not answer the question. For example, Arp has first claimed that quasars are associated with bright galaxies and subsequently found associations of quasars with companions to bright galaxies.

It should be possible to improve significantly the sensitivity of new surveys to the presence of weak clustering with respect to the previous ones, which in general were not designed to study clustering. For example, numerical simulations (Osmer 1981) show that the arrangement of 4m grism fields into a long thin rectangular strip will give much improved information on the quasar distribution on the scales of superclusters. In addition, by overlapping adjacent fields it will be possible to establish limiting magnitude differences independently of the quasar results themselves, which will also increase the detectability of weak clustering. It is important to note that large surface densities are required to investigate the distribution on supercluster scales. Consequently the 4m grism and UK Schmidt objective prism data are the best suited for work at high redshift, as they have high surface densities and favor a limited redshift range, which produces a high space density. The UK Schmidt does not yield as high a surface density, as the 4m but the large surface area covered on a single plate makes it very attractive, as there is no need to tie together several plates. The ultraviolet excess technique should not be overlooked, although to use it for the three dimensional problem will require follow up spectroscopy of a larger number of faint quasar candidates than may be required with the objective-prism approach.

At CTIO I have obtained good 4m grism plates of 21 fields near 12^h, $-11°$ to investigate just this problem. The region of the sky is previously unstudied for optically selected quasars, in contrast to much previous 4m work that has been done on regions near known quasars. An overall improvement of at least a factor of two in the detection limit for clustering may be expected for scales of 15-50 h^{-1} Mpc (present epoch). Such a limit would allow correlations of the type mentioned by Bahcall and Soneira (1982b) for superclusters to be detected if they exist in quasars at $z \sim 2$. Bahcall and Soneira estimate that the spatial correlation function for clusters of galaxies drops to unit value at 25 h^{-1} Mpc, while the new survey should be able to detect a value of 0.6 at 25 h^{-1} Mpc at the 2σ level of confidence.

As the results of this survey and those being carried out by other workers become available in the next few years, we can expect a considerable advance in our knowledge of the space distribution of large redshift quasars.

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Discussion

Wampler: 1) Did you include the redshift information in your Monte Carlo surveys, or did you check for clustering on the surface distribution without regard for redshift?

2) Doesn't your explanation for the observed increase in surface density of quasars found on 4-meter plates as compared to Curtis-Schmidt plates require surface clustering?

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Osmer: 1) Most of the work made use of the redshifts to examine the three-dimensional distribution. Although the question of surface clustering has not been thoroughly investigated, there is no obvious evidence for it.

2) You raise a very good question. The approaches I did use cannot answer it very well. Rather, an independent estimate of the surface density to be expected for the 4-m survey is needed. But I fully agree that if the surface density turns out to be high for the 4-m fields, it will be very strong evidence for surface clustering.

Inagaki: You showed the diagram of the distances versus the number of pairs. What is the pair correlation function [$\xi(r)$] of QSOs? I think that it is possible to convert the diagram to $\xi(r)$. Are there enough data to calculate the covariance function from the observed distribution of QSOs?

Osmer: Yes, I have used the correlation function to investigate if quasars cluster. Since the function gave no indication of clustering, there is as yet no information on what the covariance function actually is for quasars.

Oort: I want to stress the utmost importance of homogeneity in a survey aimed at discovering density fluctuations at large redshift (which is a most important undertaking). It should also be stressed that, in view of the huge dispersion in absolute magnitude of quasars, it is essential to obtain redshifts.

Osmer: I couldn't agree more.

Miller: The Einstein serendipitous sources already give evidence for QSO correlation on the sky. Additional X-ray sources in the field of X-ray QSO's are often QSO's (usually intrinsically faint), where such sources seldom show up in control fields. Admittedly, this is not a nice survey with control on magnitude, redshift, and so on, but it already says there are pretty strong QSO correlations on the sky.

Osmer: You raise a good point, although as you say, it is important to determine just what is expected from the control fields. It is also worth noting that the X-ray-selected quasars have lower redshifts than the ones in the optical samples I discussed.

M. Burbidge: Whereas redshifts determined from grism and objective prism plates are usually approximately correct, there is a certain proportion in which the two lines detected are not the identifications first assumed. Will you follow up any groups of QSOs found by the survey with slit spectrograms for redshift verification?

Osmer: Although I hope some progress can be made from the grism redshifts themselves, you are quite correct that followup spectroscopy will be essential.

Tyson: With an average nearest neighbor separation of 64 h^{-1} Mpc, your present survey probably would not detect the presence of clustering on scales 130 h^{-1} Mpc or less, due to undersampling.

Osmer: I do not agree that clustering could not be detected on scales smaller than 130 h^{-1} Mpc. After all, if the mean nearest neighbor distance for a sample turned out to be significantly smaller than expected, then we would conclude that clustering was present. However, it may be that little information on the nature of the clustering could be derived.