GRAVITATIONAL LENSING OF VARIABILITY SELECTED QSOs BY GALAXY CLUSTERS

L. L. Rodrigues-Williams
Astronomy Dept, FM-20, Univ. of Washington, Seattle WA 98195, USA
llrw@astro.washington.edu

M. R. S. Hawkins
The Royal Observatory, Blackford Hill, Edinburgh EH9, UK
mrsh@starlink.roe.ac.uk

ABSTRACT

Distribution and properties of QSOs behind galaxy clusters in the UKJ287 field were studied. QSOs were selected using variability criteria and are confined to $z \geq 0.4$ and $m_B \leq 19.5$. No reddening or obscuration of background QSOs due to dust in clusters is detected. A statistically significant positive angular correlation between clusters ($\langle z \rangle \simeq 0.15$) and QSOs ($0.4 \leq z \leq 2.2$) on scales of several arcminutes is found. This association of QSOs with foreground clusters is ascribed to gravitational lensing by galaxy clusters. The amplitude of associations displays trends expected if weak lensing by clusters were responsible: (a) most statistically significant associations are found for brightest QSOs found very close in projection to clusters centers; (b) QSO number excess behind clusters increases closer to cluster centers; and (c) QSO number excess increases with brighter QSO flux limit in a way that would be expected from a simple lensing model derived using Boyle, Shanks & Peterson (1988) QSO number counts and an average amplification of $A = 2$ due to clusters. The implied amplification is substantially larger than would be expected from isothermal sphere clusters with a velocity dispersion $\sigma_v \sim 1000$ km/s.

1. QSO NUMBER COUNTS

Since UKJ287 QSOs were selected using variability criteria (see Hawkins & Veron 1993, HV for details) as opposed to a more conventional color criteria it will be instructive to compare the HV and BSP (Boyle, Shanks & Peterson, 1988) QSO number-magnitude counts. The latter were UVX selected.

The HV QSO number counts are shallower than BSP at the faint end, around $m \simeq 19$. Assuming magnitude calibration is the same in both samples QSO number density at $m = 19.5$ is $5.6$ and $8.4/\sqdeg$ for HV and BSP respectively. However using the Kolmogorov-Smirnov test we cannot rule out the hypothesis that HV and BSP QSOs were drawn the same distribution. For the total numbers of HV and BSP QSOs down to $m_{lim} = 19.5—106$ and about 97 QSOs respectively—the KS test confidence level is only 67%.

2. QSO-CLUSTER CORRELATION

Galaxy cluster positions were cross-correlated with those of background QSOs ($z \geq 0.4$). In order to take into account different angular sizes of clusters angular separations between QSOs and cluster centers were calculated in terms of individual
cluster radii, then QSO-cluster separations were multiplied by the average cluster radius (0.06°) to yield degrees. Fig.1 shows two-point correlation functions for four different QSO flux cutoffs, \( m_{\text{lim}} = 18.0, 18.5, 19.0, \) and 19.5. Each point in Fig.1 represents a separation of one average cluster radius.

Clusters and (at least the bright) QSOs are seen to be positively correlated. How significant are these correlations and can they be attributed to gravitational lensing? We will explore these two questions together. We make no attempt in this paper to investigate alternative explanations of foreground cluster/background QSO associations (but see Rodrigues-Williams & Hogan 1994).

A useful way of evaluating statistical significance of such observations is with binomial statistics (see Seitz & Schneider 1994). We calculated binomial probability of having the observed number of QSOs within 0.5, 1.0, 1.5, 2.0, and 2.5 cluster radii with different QSO flux limits. The most statistically significant associations occur for QSOs within 0.5 cluster radii and with \( m_{\text{lim}} = 18.0, 18.1, \) and 18.2 (99.3%, 99.3%, and 98.6% c.l. respectively), and within 2.0 cluster radii and \( m_{\text{lim}} = 18.8 \) (98.6% c.l.). While these probabilities may not be overwhelmingly convincing by themselves there is other evidence that QSO-cluster associations are not chance associations but are due to weak lensing by clusters: (a) the most statistically significant results occurs for the brightest QSOs found closest in projection to cluster centers; (b) QSO number excess behind clusters increases closer to cluster centers, see Fig.1; (c) QSO number excess increases with brighter QSO flux limit, see Fig.1 and 2.

Thus we conclude that there is a statistically significant association between QSOs and clusters in our sample and the association is due to gravitational lensing.

3. GRAVITATIONAL LENSING

With our limited number of QSOs we cannot afford to investigate QSO overdensity as a function of distance from cluster centers. Instead, let us “fix” cluster radii at twice their cataloged values, and thus divide QSOs into “association” QSOs, i.e. those found behind extended galaxy clusters, and “field”, i.e. the rest of the QSOs. With this division association area is 17.4% of the total UKJ287 field area. Let us define overdensity, \( q \), as the ratio of the actual number of association QSOs to the number that would have been found had the field QSO number density applied to the area behind clusters.

Filled dots in Fig.2 are the observed overdensities of QSOs behind extended clusters. Error bars represent r.m.s. dispersion between clusters. We will now compare these observations with what might be expected from a simple model. Assume the clusters are uniform circular disks with constant amplification, \( A \), at an average redshift of 0.15, while QSOs are all located at large redshifts and obey BSP magnitude-number counts. This model is represented by three solid lines in Fig.2a, each for a different value of \( A \): 1.14, 2.0, and 3.0. \( A=2 \) model seems to fit the observations reasonably well.

The dashed lines in Fig.2a were obtained using the modified BSP counts: dashed lines to the left of the solid lines are the same as BSP model, except the break in the counts has been moved brightward by 0.5 mag. to \( m_{\text{break}} = 18.65 \). Similarly, the dashed lines on the right have \( m_{\text{break}} = 19.65 \), or 0.5 mag. fainter that in the BSP counts. The \( q \) vs. \( B_{\text{lim}} \) plot is sensitive to the \( m_{\text{break}} \) location, in particular, modified BSP counts with \( m_{\text{break}} = 19.65 \) are not consistent with the observations regardless of the value of \( A \).

Solid lines in Fig.2b use the number counts fit to the observed HV counts. Again, three amplifications are represented by three solid lines: \( A = 1.14, 2.0, \) and
6.0. A=6 clusters could reproduce the observations, however as we will see below such large amplifications are not characteristic of galaxy clusters.

What kind of clusters would produce observed overdensities? A back-of-an-envelope calculation shows that most clusters should not be able to generate the observed QSO overdensities. With \( \langle z_{\text{cluster}} \rangle \simeq 0.15 \) and \( \langle \theta_{\text{cluster}} \rangle \simeq 0.12^\circ \) average extended cluster radius is \( R_{\text{cluster}} \simeq 0.75h^{-1}\text{Mpc} \). \( A = 2 \) implies average surface mass density of clusters, \( \sigma \simeq 0.3 \) in terms of critical surface mass density for lensing. The latter is about 1 \( \text{gm/cm}^2 \) for lenses at \( \langle z_{\text{cluster}} \rangle \simeq 0.15 \) and sources at \( \langle z_{\text{QSO}} \rangle \simeq 1.5 \). Assuming a singular isothermal sphere model for clusters, their velocity dispersion is calculated to be \( \sigma_v \simeq 2130\text{km/s} \). This value is too high compared to observations of cluster velocity dispersions, hence clusters appear to be producing larger overdensities than expected.

What amplification would reasonable clusters be expected to produce? Using the same model as above, clusters with \( \sigma_v \sim 1000\text{km/s} \) will have \( A=1.14 \). The overdensity curves for this value of \( A \) are shown in Fig.2a,b. In both cases these are not consistent with the observations.

4. DUST IN THE UKJ287 CLUSTERS

Dust in clusters will affect background QSOs in two ways: (1) obscuration will diminish the number density of QSO behind clusters, and (2) QSOs behind clusters would be reddened. In a sample of variability selected QSOs one would not expect to “lose” QSOs to reddening. Since \( A_B \approx 4 \times E(U-B) \), obscuration is expected to be the more important of the two dust effects.

(1) Obscuration: An overdensity of QSO behind clusters is observed. Under-density is not observed at any QSO limiting magnitudes (see Fig.1), hence there is very little, if any obscuration due to dust in clusters.

(2) Reddening: All QSOs with \( z \geq 0.4 \) were divided into two samples: those behind extended clusters and the rest. The \((U-B)\) color distribution of association and field QSOs is not consistent with dust reddening by clusters. In fact, the average color of association QSOs is somewhat bluer than field QSOs.

We conclude that there is little or no smoothly distributed dust in UKJ287 galaxy clusters.

5. CONCLUSIONS

Statistically significant association between high redshift variability selected QSOs and foreground galaxy clusters were detected. The amplitude of associations displays trends expected if weak gravitational lensing by clusters were responsible: (a) most statistically significant associations are found for brightest QSOs found very close in projection to clusters centers; (b) QSO number excess behind clusters increases closer to cluster centers (Fig.1); and (c) QSO number excess increases with brighter QSO flux limit (Fig.1,2).

REFERENCES

Boyle, B. J., Shanks, T., & Peterson, B. A. 1988, MNRAS, 235, 935, BSP
Hawkins, M. R. S., & Veron, P. 1993, MNRAS 260, 202, HV
Rodrigues-Williams, L. L., & Hogan, C. J. 1994 AJ, 107, 451
Seitz, S., & Schneider, P. 1994, Preprint