A further discussion on quasar-galaxy associations from gravitational lensing

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Abstract. Quasar-galaxy associations, if they result from the effect of gravitational lensing by foreground galaxies, depend sensitively on the shape of the quasar number counts. Two kinds of quasar number-magnitude relations are predicted to produce quite different properties in quasar-galaxy associations: the counts of Boyle, Shanks and Peterson (1988; BSP) provide both positive and “negative” associations between distant quasars and foreground galaxies, relating closely with the knee (B ≈ 19.15) in these counts. However, Hawkins and Véron (1993; HV) quasar data lead to only a positive magnitude-independent quasar-galaxy association. The current observational evidence on quasar-galaxy associations, either positive or null, is shown to be the natural result of gravitational lensing if quasars follow the BSP number-magnitude relation. On the other hand, the HV counts are unable to produce the reported associations by the mechanism of gravitational lensing. It is emphasized that special attention should be paid to the limiting magnitudes in the selected quasar samples when one works on quasar-galaxy associations.

Key words: gravitational lensing – quasars: general – galaxies: general

1. Introduction

One of the important consequences of gravitational lensing, as first realized by Gott & Gunn (1974) before the discovery of the first lensed quasar pair, is that the surface number density of quasars near foreground galaxies would be increased (denoted by the quasar enhancement qG) because the distant quasars lying behind galaxies would be magnified by lensing effect of the galaxies and then enter into the detection limit (see also Canizares, 1981; Vietri & Ostriker, 1983; Schneider, 1986, 1987; Kovner, 1989; etc.). Equivalently, an overdensity of foreground galaxies around high redshift quasars would also exist (described by the galaxy enhancement qG)(Schneider, 1989). The first statistical evidence on such quasar-galaxy associations was reported by Webster et al. (1988). They claimed a significant enhancement of quasar surface density in the vicinity of galaxies. Moreover, there have been many observations of an increased number density of foreground galaxies towards distant quasar positions [for a review, see Narayan (1992)] and most of the authors confirm the galaxy number excess around background quasars. If such associations are real, gravitational lensing indeed provides a natural explanation.

However, the present observational status on the associations seems to be far from satisfactory. Table 1 summarizes the results reported in the two recent lensing meetings (Hamburg, 1991 and Liège 1993). It is noticed that (1) qG found by Magain and Van Drom has been decreased relative to the value quoted by Narayan (1992) and (2) two authors (Kedziora-Chudczer and Yee) find no evidence for foreground galaxy enhancement. Although some suggestions have been made to improve the confidence of the different results by choosing the same objects, cross-calibrating the different observing techniques and using the same criteria, large samples and considerable observing time are required to further confirm the existence of quasar-galaxy associations.

| authors      | QSO No. | selections | θ range(deg.) | qG       |
|--------------|---------|------------|--------------|----------|
| Crampton     | 101     | V < 18.5   | 0 – 6        | 1.4 ± 0.5|
|              |         | z > 1.5    |              |          |
|              |         | V < 18.5   | 6 – 90       | ~ 1      |
|              |         | z > 0.65   |              |          |
|              |         | V = 17.4   | 0 – 3        | ~ 2.8    |
|              |         | (z) = 2.3  |              |          |
| Magain       | 153     | V = 17.4   | 3 – 13.7     | ~ 1.46   |
|              |         | (z) = 2.3  |              |          |
| Van Drom     | 136     | V < 18     | 3 – 10       | ~ 2      |
|              |         | 0.7 < z < 2.3 |        |          |
|              |         |              |              |          |
| Webster      | 68      | V < 19     | 2 – 6        | 1.0 ± 0.3|
|              |         | z > 1.5    | 2 – 10       | 1.0 ± 0.2|
|              |         |              | 2 – 15       | 0.9 ± 0.1|

Nevertheless, observations have already provided some important implications for quasar-galaxy associations, and some valuable information can be obtained if one reaches a better understanding of their mechanism – gravitational lensing. The second effect of gravitational lensing is the area distortion

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which reduces the magnitude of the first effect (magnification), leading to a lower surface number density of sources (quasars) (Gott & Gunn, 1974; Peacock, 1986; Narayan, 1989). Consequently, a large enhancement is hard to reach. All the previous authors have paid their attentions to how to find the maximum enhancement factor \( q_Q \) or \( q_R \). In 1989 Narayan (1989) developed an elegant formula for the calculation of \( q_Q \) and Kovner (1989) discussed the upper bound on the evaluation of \( q_Q \). However, one important fact has been neglected: that null and even “negative” associations between high redshift quasars and low redshift galaxies would also occur in some cases. That is to say, instead observing an overdensity of quasars around foreground galaxies, one may detect a number decrease of quasars in the vicinity of foreground galaxies, i.e., \( q_Q < 1 \). In fact, Narayan (1989) has showed such an example in his figure with \( B_0 = 20 \) and Kovner (1990) has also mentioned the case of \( q_Q < 1 \) for fainter counts, but they both didn’t further discuss this effect. As will be shown below, these null and/or “negative” associations play an important role in the understanding of the observed associations between quasars and galaxies.

2. The dependence of \( q_Q \) on quasar number counts

The quasar enhancement factor \( q_Q \) is the ratio of the observed quasar surface number density around foreground galaxies to their background mean value, which depends on (1) quasar number counts \( N(< m) \) and (2) magnification \( A \) by lensing effect of the galaxies (Narayan, 1989)

\[ q_Q = \frac{N(< m + 2.5 \log A)}{N(< m)} \frac{1}{A}. \]

where \( 2.5 \log A \) is the increased apparent magnitude by the first effect of lensing which leads to picking up the fainter quasars around foreground galaxies, and \( 1/A \) represents the factor of the distorted area by second lensing effect of the galaxies, resulting in a decrease of quasar number density.

Since \( q_Q \) is closely related to the quasar number-magnitude relation \( N(< m) \), a precise determination of \( N(< m) \) is required for the theoretical study of quasar-galaxy associations. On the other hand, one may test the reported \( N(< m) \) in different observations by using the evidence of quasar-galaxy associations. Essentially, two kinds of quasar number-magnitude relation have been thus far suggested from, respectively, the survey of Boyle, Shanks and Peterson (1988) (BSP) and the survey of Hawkins and Véron (1993) (HV). The significant difference in these two relations is that the slope of the BSP counts changes at \( B \approx 19.15 \) from 0.86 to 0.28 while there is no such a turnover in the range of \( B \leq 21 \) in the HV counts. Interestingly, the subsequent surveys by the BSP group, including the recent X-ray observations, have all confirmed the existence of the flattening of \( N(< m) \) at fainter magnitude (Boyle et al., 1990; Boyle, Jones & Shanks, 1991; Zitelli et al., 1992; Boyle et al., 1993).

We will adopt these two kinds of quasar number-magnitude relations in the following computations and compare their properties in the resulted quasar-galaxy associations. The BSP cumulative counts have been fitted by Narayan (1989) to be

\[ \begin{align*}
N(< B) &= 4.66 \times 10^{0.86(B-19.15)}, \quad B < 19.15; \\
N(< B) &= -10.95 + 15.61 \times 10^{0.28(B-19.15)}, \quad B > 19.15.
\end{align*} \tag{2}
\]

This relation is valid for \( z \leq 2.2 \) and \( B \leq 21 \). However, a later observation (Boyle, Jones & Shanks, 1991) indicates that eq.(2) holds true also to \( B \leq 22 \). The HV cumulative counts can be fitted by

\[ N(< B) = 6.25 \times 10^{0.51(B-19.15)}. \tag{3} \]

This relation has been written in such a form that its slope can be directly compared with the corresponding values of the BSP counts.

The enhancement \( q_Q \) is plotted against the magnification \( A \) in Fig.1 for both BSP and HV counts. One should pay a special attention to the case where \( m + 2.5 \log A \) is larger than the quasar sample threshold. For instance, the BSP and the HV surveys were limited to \( B \leq 21 \). Therefore, the number-magnitude relation \( N(< B+2.5 \log A) \) would fail when \( B + 2.5 \log A > 21 \), and one cannot calculate the enhancement \( q_Q \) beyond the survey limit: this sets a strong constraint on the application range of eq.(1). Thus, the conclusions of Narayan (1989) should be taken cautiously, and in strict sense his arguments are valid only for these solid lines in Fig.1 rather than the whole magnification range. The extrapolation of the solid lines requires the knowledge of fainter quasar counts.

![Fig. 1.](image-url) The quasar enhancement \( q_Q \) against the quasar limiting magnitude \( B \) and the lensing magnification \( A \) for the BSP and the HV counts. The solid lines correspond to the results within the survey threshold of \( B = 21 \) and the dotted lines are the extrapolated results of \( N(< B) \) beyond \( B = 21 \). Note that in the HV counts, \( q_Q \geq 1 \), providing always the positive associations, while in the BSP counts \( q_Q \) may be smaller than 1 when \( B > 19 \), resulting in the “negative” associations.

A power-law number-magnitude relation with index of \( \alpha \), \( N(< m) \sim 10^{\alpha m} \), would lead to an enhancement of \( A^2 \alpha^{-1} \), independent of the limiting magnitude. The HV counts show that \( \log q_Q / \log A = 0.3 \). Hence, it is unlikely that a large enhancement factor \( q_Q \) can be reached in the HV counts. For example, \( q_Q > 4 \) requires the lensing magnification to be greater than 100, which cannot be produced by a normal galaxy. Nevertheless, the HV counts do not result in the “negative” associations, i.e., \( q_Q \geq 1 \).

An example of the “negative” association with \( q_Q < 1 \) has been shown in Fig.1, the curve with \( B = 20 \) from the BSP counts. In fact, in the range of \( 1 < A < 100 \) the negative
cases may occur for the limiting magnitude \( B > 19 \). The reason for this is that the BSP counts turn to be strongly flatter after \( B = 19.15 \), which would depress significantly the effect of “picking up” the fainter sources, while the second effect of lensing remains unchanged. As a result, one may observe a “negative” association between the background quasars and the foreground galaxies. Note that \( q_Q \) is not very sensitive to the selection of the brightness of the foreground galaxies which contribute only lensing magnifications.

3. Galaxies as deflectors

For simplicity we adopt a singular isothermal sphere for matter distribution in a lensing galaxy. The magnification in this model can be simply written as

\[ A = \frac{\theta}{\theta - \theta_e}, \]

where \( \theta \) is the distance to the center of the galaxy on the galaxy plane and \( \theta_e \), the Einstein radius

\[ \theta_e = 4\pi \left( \frac{\sigma}{c} \right)^2 \frac{D_{ds}}{D_s}. \]

Here \( \sigma \) is velocity dispersion in the galaxy. \( D_{ds} \) and \( D_s \) measure the angular diameter distances from the galaxy and from the observer to the distant source, respectively. The observations which search for quasar-galaxy associations often choose galaxies at relatively lower redshift \((z < 0.3)\) and quasars at higher redshift \((z \approx 2)\). Therefore, the distance parameter \( D_{ds}/D_s \) is nearly unity. This is particularly true for the nearby galaxies. Anyhow, considering the actual distances does not significantly change the following calculations. For a typical nearby galaxy,

\[ \theta_e = 1.52 \left( \frac{\sigma}{230 \text{km/s}} \right)^2. \]

Fig.2 shows the enhancement \( q_Q \) against the search ranges around foreground galaxies at different limiting magnitudes \( B \). It has been presumed that the extrapolation of both BSP and HV counts to the fainter magnitude \((B > 21)\) is reasonable. Since \( q_Q \) is independent of limiting magnitude in the HV counts, the resulted \( q_Q \) relates only with the search areas. For a typical galaxy, \( q_Q \) is relatively small even when one focuses on the area very close to the galaxy center. Therefore, at least two results shown in Table 1 can not be explained by the HV counts, Magain’s \( q_Q \sim 2.8 \) within 3” and Webster’s \( q \sim 2 \) in the radius of 3 – 10”.

One may argue that a larger velocity dispersion may provide a higher magnification, leading to the increase of \( q_Q \) in terms of eq.(1). However, this would simultaneously produce a larger Einstein radius \( [\text{eq.}(6)] \), within which the primary image of the lensed quasar does not appear. The occurrence of the secondary image within the Einstein radius is accompanied by the multiple images, which are very rare in searches for the quasar-galaxy associations.

The most interesting result from the BSP counts is that both positive and “negative” associations can occur, separated in the range of \( 19 < B < 20 \). Several important conclusions are as follows: (1)The positive associations between foreground galaxies and background quasars would be found when one chooses the threshold of the quasar sample to be brighter than \( B \approx 19.5 \). In particular, \( q_Q \) is nearly independent of the limiting magnitude \( B \) if \( B \) is smaller than 18.5 for \( \theta < 3" \) and 19 for the larger search areas around galaxies. (2)When the fainter quasars \((B > 19.5)\) are involved in the sample for the purpose of finding the quasar-galaxy associations, one would expect to detect null and/or “negative” associations. Similar to the positive cases, the strong “negative” association \((q_Q < 1)\) would be found if one looks for the ranges very close to the galaxy centers. Note that the values of \( q_Q \) in all the fainter cases are actually close to 1 and therefore, one would simply have \( q_Q \approx 1 \), i.e., the null association, if errors in the observations were significant.

Certainly, Fig.2 is only for a galaxy with a constant velocity dispersion of 230 km/s. A more precise treatment is to consider galaxy luminosity distribution, e.g., the Schechter luminosity function, and then to derive the galaxy distribution in velocity dispersion by using a luminosity-velocity dispersion law, e.g., the Faber-Jackson relation. We notice, however, that different galaxies can only lead to the vertical shifts in amplitude in Fig.2 and the main features would remain unchanged.

4. Explanations of the present evidences

It is generally believed that the foreground galaxy enhancement factor \( g_Q \) should be in principle equal to the background quasar enhancement factor \( q_Q \). The results on quasar-galaxy associations \((q_Q)\) listed in Table I, despite their large discrepancies, are in fact consistent with the lensing predictions \((q_Q)\)

\[ q_Q \approx 1.5 \text{ at } \theta < 3" \]

Fig. 2. The quasar enhancement factors \( q_Q \) over different search areas around a foreground galaxy with \( \sigma = 230 \text{ km/s} \). The curves have been extrapolated to the fainter magnitudes.
from the BSP quasar number counts. To see this, one needs to translate the V magnitudes in the observational studies of quasar-galaxy associations into the B magnitudes in the theoretical predictions from lensing. We take \((B - V) \approx 0.4\) for distant quasars, as suggested by P. Vérон (private communication).

The Crampton result of \(q = 1.4 \pm 0.5\) was obtained with a \(B\) limiting magnitude of \(\sim 18.9\). The BSP prediction in Fig.2 provides the same value of \(\sim 1.4\) within \(\theta = 6^\circ\) at \(B \sim 19\).

Kedziora-Chudczer kept the same limiting magnitude as Crampton but searched a larger range of separations. One can see from Fig.2 that around \(B \sim 19\) an average value over \(\theta = 6-90^\circ\) tends to close to unity, roughly consistent with the observation.

Magain’s value is the highest one, \(q = 2.8\). However, he chose the brightest quasars and the smallest search range \((\theta \leq 3^\circ)\). At \(B \approx 18\) and \(\theta = 3^\circ\), lensing predicts that \(q = 2.3\). Considering the large error bar in his data (Narayan, 1992), the reported \(q\) is within the prediction of Fig.2.

With the same limiting magnitude, Van Drom’s observations were made for a larger radius. His finding of \(q = 1.46\) fits quite well to the value in Fig.2.

Between \(\theta = 3^\circ\) and \(\theta = 10^\circ\), Webster found that \(q \sim 2\) at \(B_{limat} \sim 18.4\). The predicted results are \(1.3 < q < 2.3\) over these areas.

Finally Yee’s negative or null evidences are the natural results of the faint limiting magnitude used in his quasar samples \((B \sim 19.4)\). As one can clearly see, around \(B = 19.5\) the “turnover” occurs despite the search radii. Therefore, the enhancements are expected to be roughly unity (i.e., the null or “negative” associations) for all of his observations.

However, it should be mentioned that the threshold in each quasar sample for searches of quasar-galaxy associations was not actually very well defined and setting a clear limiting magnitude in each observation is rather difficult. Additionally, using a mean value for the limiting magnitude in the survey often makes it hard to compare with the theoretical predictions. Moreover, the presently known enhancement factors may contain large errors and uncertainties, and therefore, the above explanations of their gravitational lensing origin still needs to be further investigated.

5. Conclusions

BSP and HV quasar counts show significantly different behaviors in quasar-galaxy associations, providing an efficient way to test the proposed quasar number-magnitude relations. Consequently, the present observational evidences for these associations seem to contradict the predictions from the HV counts while they are very well fitted by the BSP data, confirming the turnover at \(B \approx 19.15\) in quasar counts. However, this conclusion should be considered to be preliminary, depending on the significances of the reported enhancement factors for quasar-galaxy associations.

The gravitational lensing origin of quasar-galaxy associations has been found to be the natural explanations for all the reported evidences, either positive or null (negative). It is pointed out that the quasar limiting magnitude in the survey for quasar-galaxy associations plays an important role: The positive association would be found for the \(B_{limat} < 19.5\) quasar samples and the negative result, for the \(B_{limat} > 19.5\) ones. This conclusion is independent of the search ranges, no matter how close the galaxies (quasars) are chosen to the quasar (galaxy) positions.

It is expected that the fainter quasar samples \((B > 20)\) would provide some further evidences on the gravitational lensing origin of quasar-galaxy associations. The confirmation of the “negative” associations between foreground galaxies and faint background quasars would set very useful constraints on the shape of quasar number-magnitude relation. Moreover, eq.(1) is actually a universal relation for finding the enhancements by gravitational lensing. A future work is to apply eq.(1) for background galaxies, which may provide very useful information on 3CR galaxy-galaxy associations (Hammer & Le Fèvre, 1990), 3CR galaxy-cluster associations (Roberts, O’Dell & Burbidge, 1977; Hammer & Le Fèvre, 1990) and also the possible optical galaxy-cluster associations, especially for K-selected galaxies. Recall that the associations, either positive or negative, between foreground objects and background sources may occur if the slope of \(\log N/\log m\) for background sources is not exactly equal to 0.4.

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