

A study of six low-redshift quasar pairs

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ABSTRACT

The dynamical properties of six Sloan Digital Sky Survey quasar pairs at $z \leq 0.8$ are investigated. The pairs have proper transverse separation $R_{\perp} \leq 500$ kpc, and velocity difference along the line of sight $\Delta V_r \leq 500$ km s⁻¹. If they are bound systems their dynamical mass can be evaluated and compared with that of host galaxies. Evidence is found of an excess of the former mass with respect to the latter. This suggests that these quasar pairs are hosted by galaxies with massive dark haloes or that they reside in a group/cluster of galaxies.

Key words: quasars: general.

1 INTRODUCTION

Quasars (hereafter QSO) are rare and short-lived objects (e.g. Martini 2004; Hopkins et al. 2005), nevertheless a number of associations of QSOs have been discovered in the last decades (e.g. Shaver 1984; Djorgovski 1991; Zhdanov & Surdej 2001). The study of these systems is important in the understanding of the evolutionary history of galaxies with cosmic time and the mechanism of QSO ignition (e.g. Di Matteo, Springel & Hernquist 2005; Foreman, Volonteri & Dotti 2009). Particular interest has been dedicated to binary QSOs, i.e. two QSOs that reside in the same galaxy and that are characterized by the presence of double systems of emission lines (e.g. Boroson & Lauer 2009; Rosario et al. 2011). These systems are thought to form in the last stages of a major merger event (e.g. Colpi & Dotti 2009, and references therein).

The search of QSO pairs (QSOPs) at scales from tens to hundreds of kiloparsecs in large surveys was mainly focused on the investigation of QSO clustering properties (e.g. Hennawi et al. 2010; Shen et al. 2010) and in particular on the excess, with respect to the large-scale extrapolation, found at separations of tens of kiloparsecs (e.g. Hennawi et al. 2006; Myers et al. 2007, 2008). The study of the clustering allows us to estimate the bound mass of the structures inhabited by QSOs (e.g. Croom et al. 2005; Shen et al. 2010), but little attention has been given thus far to the study of the dynamical properties of single QSOPs that, if isolated, are dominated by the mass of their host galaxies (e.g. Brotherton et al. 1999; Mortlock, Webster & Francis 1999). Although the cold dark matter models of galaxy formation predict that QSOs, and in particular QSOPs, reside preferentially in particularly rich environments (e.g. Efstathiou & Rees 1988; Hopkins et al. 2008), some observational evidence

shows that QSOPs could be isolated systems (e.g. Fukugita et al. 2004; Boris et al. 2007).

In this paper we look for QSOPs in the Sloan Digital Sky Survey (SDSS; York et al. 2000), with the goal of reconstructing the systemic dynamics of the pairs. We found six QSOPs at redshift < 0.8 , for which the measurement of [O III] lines allows us to pursue this study. In Section 2 we describe our sample. Section 3 deals with measurements of radial velocity differences. In Section 4 we compute virial masses and compare them with those of the host galaxies. We investigate the QSOP environment in Section 5. Implications of our results are discussed in Section 6.

Throughout this paper, we consider a concordance cosmology with $H_0 = 70$ km s⁻¹ Mpc⁻¹, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$.

2 THE QUASAR PAIR SAMPLE

We investigate the catalogue of spectroscopically confirmed QSOs constructed by Schneider et al. (2010) on the basis of the SDSS DR7 (Abazajian et al. 2009) which contains $\sim 100\,000$ objects. We select as pairs two QSOs that have proper transverse separation $R_{\perp} \leq 500$ kpc, and radial velocity difference $\Delta V_r \leq 500$ km s⁻¹, as based on SDSS redshifts. 14 pairs that satisfy the above criteria are found in the redshift range $0.5 \lesssim z \lesssim 3.3$, with luminosities between $M_V \sim -22$ and $M_V \sim -25$.

Since we are interested in the dynamical properties of these systems, we also require that the forbidden [O III] lines, which are used to measure the systemic velocity of the QSOs (see Section 3), are present in the SDSS spectra. This implies that the candidate QSOPs are at redshifts below 0.8. With this additional condition we obtain a list of six pairs of radio quiet QSOs (see Table 1), five of them considered also by Hennawi et al. (2006).

The probability that they are chance superpositions is rather low. In fact, searching for QSOPs in a random sample generated with the redshift permutation method (e.g. Osmer 1981; Zhdanov & Surdej 2001), which consists of maintaining the position of the QSOs fixed,

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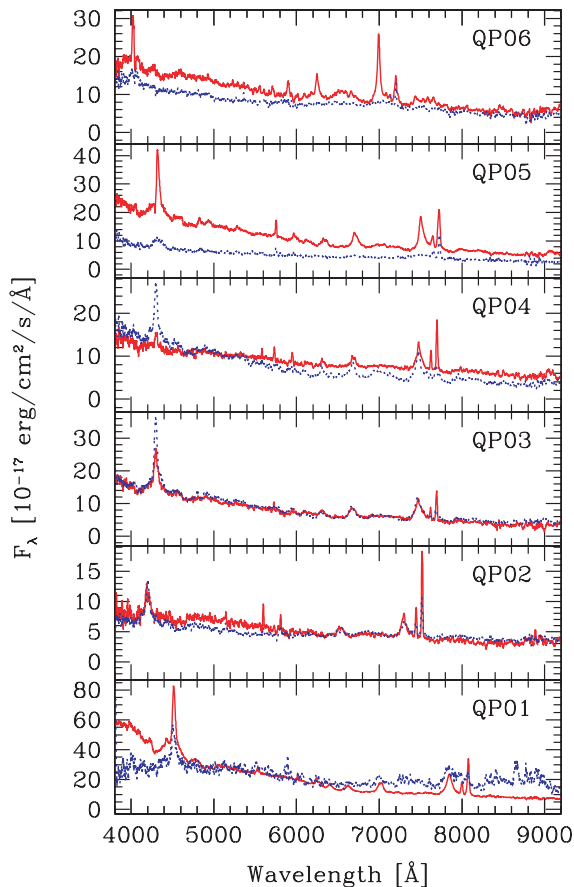
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Table 1. Properties of selected QSOPs. z is the redshift from Schneider et al. (2010), M_V is the absolute magnitude in V band, $\Delta\theta$ and R_\perp are the angular and proper transverse separation, and ΔV_r is the radial velocity difference derived from the redshifts given in the catalogue.

ID	Name	QSO A		QSO B		$\Delta\theta$ (arcsec)	R_\perp (kpc)	ΔV_r (km s ⁻¹)
		z	M_V (mag)	z	M_V (mag)			
QP01	SDSS J0117+0020AB	0.6122	-22.38	0.6130	-24.65	44	300	149
QP02	SDSS J0747+4318AB	0.5010	-22.76	0.5012	-22.61	9	56	40
QP03	SDSS J0824+2357AB	0.5356	-23.19	0.5365	-23.19	15	94	176
QP04	SDSS J0845+0711AB	0.5363	-23.48	0.5373	-23.20	62	393	195
QP05	SDSS J0856+5111AB	0.5425	-22.81	0.5434	-23.59	22	139	175
QP06	SDSS J1249+4719AB	0.4375	-23.09	0.4382	-22.63	79	446	146

but to randomly permute the redshift, we expect to find ~ 0.4 such pairs compared to the six observed. Note that in this new sample most of the correlations between objects are destroyed, but the angular correlation between QSOs is preserved, so the result can be considered as an upper limit for the number of chance QSOPs. Thus we assume that all these QSOP are physically associated.

We can exclude that these QSOPs are gravitational lens images because significant differences in the spectra of the two QSOs are apparent (see Fig. 1), wide separation ($\Delta\theta > 3$ arcsec) lensed QSOs are quite rare (Kochanek, Falco & Muñoz 1999) and there is no evidence in SDSS images for luminous galaxies in the foreground of QSOPs that could act as a lens.

**Figure 1.** The SDSS spectra of the two QSOs of each pair (background red solid line, foreground blue dotted line). Data are smoothed with a 10 Å boxcar filter. In order to make visible the features of the spectrum of the foreground QSO of QP01, its flux is increased by a factor of 10.

3 VELOCITY DIFFERENCES FROM [O III] LINES

We can also exclude the possibility that the velocity differences can be related to the Hubble flow and therefore measure the physical distance of the pairs. In fact, we verify that, under this hypothesis, in the Schneider et al. (2010) QSO catalogue there are 35 pairs with $R_\perp \leq 4$ Mpc and physical radial separation $R_\parallel \leq 4$ Mpc. Assuming that the 29 systems with $R_\perp > 0.5$ Mpc are homogeneously distributed, we expect ~ 1 with $R_\perp \leq 0.5$ kpc, while six are found.

It is well known that the redshifts of QSOs derived from emission lines of various elements can differ by as much as 1000 km s⁻¹ (e.g. Tytler & Fan 1992; Bonning, Shields & Salvander 2007). Therefore, the most reliable estimate of the systemic velocity of the QSOs is obtained from the measurements of narrow forbidden lines, such as [O III]_{λ4949} and [O III]_{λ5007} (e.g. Nelson & Whittle 1996; Nelson 2000; Boroson 2005; Hewett & Wild 2010).

We evaluate the barycentres of the lines considering the flux above various thresholds with respect to the peak flux (see Fig. 2). We take the line position to be the median of the individual measurement of the barycentre, and the corresponding uncertainty is given by their interquartile range. The redshifts and the radial velocity differences that result from these measurements are reported in Table 2.

4 THE MASS OF QSO PAIRS

Assuming that the QSOPs form bound systems and thus that the velocity difference measured is due to the mutual interaction between the two QSOs, we can infer the dynamical mass through the virial theorem:

$$M_{\text{vir}} = \frac{\Delta V^2 R}{G}, \quad (1)$$

where ΔV is the relative velocity of the two components, R their separation and G the gravitational constant. For circular orbits, it is possible to calculate the radial component of the relative velocity (ΔV_r) from the redshift difference (Δz). One has

$$M_{\text{vir}} = C \left(\frac{c \Delta z}{1+z} \right)^2 \frac{R_\perp}{G}, \quad (2)$$

where c is the speed of light, R_\perp the proper transverse separation of the pair (see Table 1), and the factor C depends only on the inclination angle of the orbital plane, ι , and on the phase angle, ϕ , and is given by

$$C^{-1} = (\sin \phi \sin \iota)^2 \sqrt{\sin^2 \phi + \cos^2 \phi \cos^2 \iota}. \quad (3)$$

The average values of C is $\langle C \rangle = 3.4$ and the minimum value is $C_{\text{min}} = 1$.

Table 2. Radial velocity difference and virial mass of the QSOPs. z_n is the redshift measured from the [O III] narrow emission lines, $\Delta V_r(n)$ is the corresponding radial velocity difference and $M_{\text{vir}}(\text{min})$ is the minimum virial mass compatible with the uncertainties of the measure of $\Delta V_r(n)$.

ID	$z_n(A)$	$z_n(B)$	$\Delta V_r(n)$ (km s ⁻¹)	$M_{\text{vir}}(\text{min})$ (10 ¹² M _⊙)
QP01	0.61142 ± 0.00078	0.61341 ± 0.00001	370 ± 171	2.8–20.4
QP02	0.50108 ± 0.00003	0.50174 ± 0.00001	132 ± 7	0.2–0.3
QP03	0.53527 ± 0.00009	0.53678 ± 0.00002	295 ± 21	1.6–2.2
QP04	0.53509 ± 0.00015	0.53754 ± 0.00002	478 ± 35	17.9–24.0
QP05	0.54322 ± 0.00003	0.54239 ± 0.00003	161 ± 9	0.7–0.9
QP06	0.43861 ± 0.00045	0.43859 ± 0.00001	4 ⁺⁹⁴ ₋₄	–

In Table 2 we report for each QSOP the minimum virial mass [$M_{\text{vir}}(\text{min})$, corresponding to $C = 1$], which represents the minimum mass of the system to be bound. In the case of QP06, since there is no significant difference of radial velocity, we cannot estimate its virial mass. In this case, we are probably observing the pair orbit nearly face-on.

It is of interest to compare these $M_{\text{vir}}(\text{min})$ with the expected total mass of the pair based on the mass of their host galaxies. According to available measurements of QSO host galaxies (e.g. Kotilainen et al. 2009, and references therein) it is found that their mass changes little with redshift. The typical range of host mass,

based on the galactic luminosity, for objects at $z < 1$ is $\sim 0.3\text{--}1.3 \times 10^{12} M_{\odot}$ (Decarli et al. 2010, and references therein).

While for three QSOPs (QP02, QP03 and QP05) their $M_{\text{vir}}(\text{min})$ is consistent with that expected by the typical host galaxy masses, in two cases (QP01 and QP04) the minimum virial mass is substantially larger than that of their host galaxies (see Table 2). If one assumes the average value of C ($C = 3.4$) instead of its minimum, then the above cases are further strengthened and also QP03 would exhibit a significant mass excess. For the whole (small) sample the median value for the M_{vir} is $6.5 \times 10^{12} M_{\odot}$.

A possible explanation for this mass excess is that QP01 and QP04 belong to a group or a cluster of galaxies. In this case, in fact, the measured velocity difference depends on the overall mass distribution. In the next session we investigate this possibility.

5 QSO PAIRS' ENVIRONMENT

We searched the SDSS *i*-band images for an overdensity of galaxies that could justify the mass excess discussed above. The SDSS magnitude limit in this band is 21.3 mag (York et al. 2000), thus it allows us to reach $\sim (M^* + 1)$, where $M^* = -20.5$ at $z = 0.5$ (Wolf et al. 2003), therefore these images permit us to detect only the bright part of the galaxy luminosity function.

The galaxy search was performed using SExtractor (Bertin & Arnouts 1996) on the SDSS images in an area of 4 Mpc around each pair. The threshold limits for the detections are set at 1.5 times over the rms of the background, and we classified as *galaxy* all the sources with the STARCLASS parameter lower than 0.2. The number of galaxies in the fields (see Table 3) is consistent with the expectation from the study performed up to $I = 24$ mag by Postman

Table 3. Environment of QSOPs. $n(\text{bkg})$ is the density of galaxies in the region between 2 Mpc and 4 Mpc, $N(<0.5 \text{ Mpc})$ is the number of galaxies in the inner 500 kpc, and $n(<0.5 \text{ Mpc})$ is the corresponding density. M/L is the minimum mass-to-light ratio that could have a galaxy cluster detected on SDSS *i*-band images (3σ over the background). The associated uncertainties represent the 1σ statistical fluctuations.

ID	$n(\text{bkg})$ [arcmin ⁻²]	$N(<0.5 \text{ Mpc})$	$n(<0.5 \text{ Mpc})$ [arcmin ⁻²]	M/L
QP01	1.2 ± 0.2	5	1.4 ± 0.6	$\gtrsim 30$
QP02	1.4 ± 0.1	8	1.4 ± 0.5	$\gtrsim 3$
QP03	2.1 ± 0.1	26	4.7 ± 0.9	$\gtrsim 2$
QP04	1.9 ± 0.1	15	2.7 ± 0.7	$\gtrsim 100$
QP05	1.8 ± 0.2	5	0.9 ± 0.4	5
QP06	1.9 ± 0.2	12	2.3 ± 0.7	...

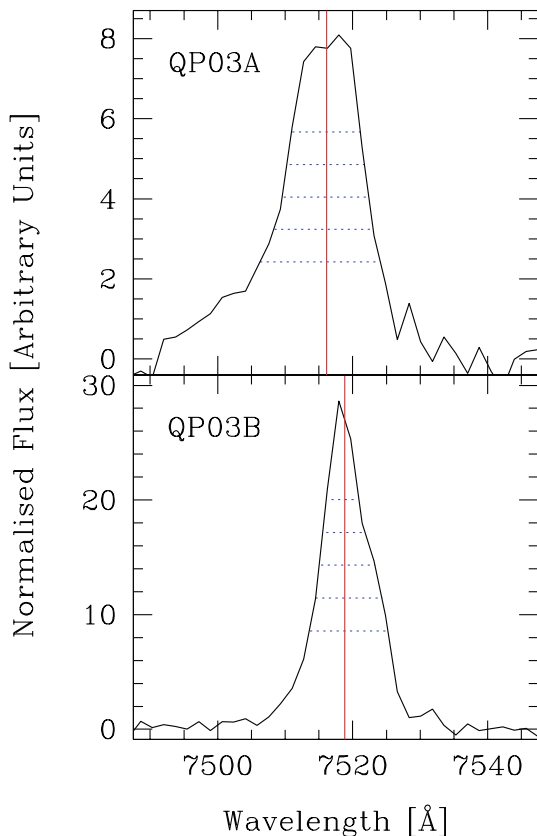


Figure 2. The normalized SDSS spectra of the two QSOs of the pairs QP03 in the region around the emission line [O III] at $\lambda = 5007 \text{ \AA}$. The central value (red vertical lines) is the median value of the barycentre calculated considering different thresholds of line peak flux (i.e., 30, 40, 50, 60 and 70 per cent, blue dotted horizontal lines).

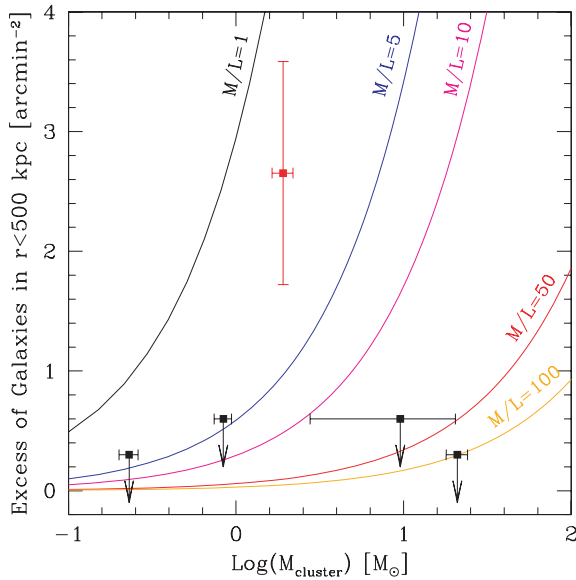


Figure 3. Expected central density of galaxies in SDSS *i*-band images as a function of the mass of the clusters for various value of the M/L ratio (filled lines). Black square points are the QSOPs for which no significant evidences of an overdensity of galaxies are present. For these systems we assume that, if a cluster is present, it must have a density $< 3\sigma$ the variation of the background. The red square point indicates the pair QP03, for which SDSS images highlight a significant overdensity of galaxies in the first 500 kpc from the QSOP.

et al. (1998) on a region of $4^\circ \times 4^\circ$, and the number of galactic stars with the prediction of the TRILEGAL package¹ by Girardi et al. (2005).

In order to highlight a possible overdensity around the QSOPs, we compute the number of galaxies in annuli of 500 kpc radius, starting from the centre of each pair. We then compare the galaxy density in the first 500 kpc with that in the region between 2 and 4 Mpc, assumed as background. These values are reported in Table 3. Only QP03 shows a significant overdensity of galaxies. In the other cases there is no evidence for a galaxy excess above the background by more than 3σ .

We evaluate the expected density of galaxies brighter than the SDSS luminosity limits ($i \sim 21.3$ mag) if a cluster of mass $M_{\text{tot}} = M_{\text{vir}}(\text{min})$ were associated with the QSOPs. We assume that the galaxies of the cluster follow the Schechter luminosity function with parameters given by Wolf et al. (2003), and that the galaxies are distributed according to a King profile with a virial radius calculated from the virial mass following the relations reported by Girardi et al. (1998).

We compare the expected galaxy density with that observed in SDSS images (see Fig. 3). In all cases but one, we do not find indications for overdensities larger than three times the variation of the background, thus, to explain the minimum virial masses of the pairs, these systems require a mass-to-light ratio, $M/L \gtrsim 5\text{--}100$ (see Table 3). Note that these values are comparable with those reported in various studies on dynamical properties of galaxy clusters (e.g. Popesso et al. 2005, and references therein).

¹ http://stev.oapd.inaf.it/cgi-bin/trilegal_1.4

6 CONCLUSIONS

The analysis of the properties of six low-redshift QSOPs has shown that in at least two cases the dynamical mass of the pair exceeds, by a factor $\gtrsim 10$, that expected from their host galaxies. A possible explanation of this excess is that the QSO host galaxies are surrounded by dark matter haloes with masses similar to those found in massive ellipticals (e.g. Napolitano et al. 2009). Alternatively, the observed velocity differences could be due to the presence of a cluster or a group of galaxies associated with the QSOPs. An analysis of SDSS *i*-band images shows evidence for a significant overdensity of galaxies in only one case. For the other systems, a lower limit to the M/L ratio was determined at $M/L \gtrsim 5\text{--}100$ for galaxy clusters with masses equal to the virial masses of the pairs.

In order to strengthen the evidence of a mass excess, we can consider a larger sample given by the lists of already known QSOPs (Hennawi et al. 2006, 2010; Myers et al. 2008; Schneider et al. 2010). Most of these systems are at $z > 0.8$, excellent instrument capabilities are thus required to perform these studies.

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