Part 2

Cluster Scale Halos with Weak and Strong Lensing

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Galaxy Groups towards Lensed Quasars

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Abstract. In this proceeding we present the method and results of the search for galaxy groups or clusters in the vicinity of the line-of-sight towards lensed quasars.We have studied a sample of ten quasars, using deep ESO/VLT FORS1 and ISAAC images, as well as archive HST/WFPC2 and NiCMOS data. We find that there is most probably a galaxy group towards CTQ 414, HE 0230-2130, B 1359+154, H 1413+117, SBS 1520+530 and HE 2149-2745, with masses $\leqslant 4\ 10^{14} \mathrm{M}_{\odot} \mathrm{h}^{-1}$. Considering its photometric redshift, the galaxy group discovered in the field around HE 1104-1805 is associated with the quasar rather than with the lensing potential. We also conclude that the pair LBQS 1429-0053-A and LBQS 1429-0053-B is a genuine binary quasar rather than a lensed quasar.

1. Introduction

Gravitational lensing of distant quasars is a powerful tool for addressing cosmological and astrophysical questions. These include the distribution of dark matter in galaxies (Keeton, Kochanek & Falco 1998), the determination of the Hubble parameter H_0 through the measurement of the time delay between the quasar image light curves (Refsdal 1964), as well as the measurement of the value of the cosmological constant Λ (Kochanek 1996). All the complexity in resolving these questions is due to the difficulty in modeling the lensing potential. Until now, most of the multiply imaged quasars were thought to be lensed by one main and single lensing galaxy, disregarding the local environment. Yet, while modeling these systems, it has been realized that the addition of an "external shear" contribution is mandatory in many cases to reproduce the observations (Keeton, Kochanek & Seljak 1997). It is now known that in at least one quarter of the cases the lensing potential is much more complex than a single lensing galaxy and that it is associated with a galaxy cluster or a galaxy group.

In this proceeding we present a summary of the study of the fields around ten quasars: nine lensed systems and one for which the lensed nature was uncertain at the beginning of this investigation. In Sect. 2 we present the observations and in Sect. 3, the quasar sample. The method developed to search for galaxy groups is detailed in Sect. 4, while the results are presented in Sect. 5. Finally we give our conclusions and prospectives in Sect. 6.

2. The dataset

The SBS 1520+530 quasar was observed at the NOT†/Alfosc (R- and V- band), that provide a wide field-of-view around the quasar images (6.5'×6.5'). For a better signal-to-noise ratio, these images are combined with NOT/Hirac V- and R-band data. Hirac I-band data as well as NiCMOS F160w images are used to complete the dataset to do a multi-color analysis. A summary of the quality of the data is given in Faure *et al.* (2002).

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Table 1. Some properties of the lensed quasars. Column 1: quasar name. Columns 2, 3: right ascension and declination of quasar image A (J2000). Column 4: quasar redshift. Column 5: lensing galaxy redshift, where "?" means "unknown" and "(p)" means "photometric redshift". Column 6: size of the system corresponding to the maximal angular separation between the quasar images (in arcsecond). Column 7: system configuration.

Quasar	RA	DEC	z_{qso}	z_{lens}	Size	Config.
CTQ 414	$01^h58^m41.43^s$	-43°25'3.4"	1.29	?	1.22"	double
HE 0230-2130	$02^h32^m33.1^s$	-21°17'26"	2.16	$\leqslant$1.6	2.10"	quadruple
LBQS 1009-0252	$10^h12^m15.71^s$	-03°07'02"	2.74	0.88(p)	1.54"	double
B 1030+074	$10^h33^m34.08^s$	+07°11'25.5"	1.54	0.599	1.56"	double
HE 1104-1805	$11^h06^m33.45^s$	-18°21'24.2"	2.32	0.73	3.19"	double
B 1359+154	$14^h01^m35.55^s$	+15°13'25.6"	3.235	?	1.71"	sextuple
H 1413+117	$14^h15^m46.40^s$	+11°29'41.4"	2.55	0.9(p)	1.10"	quadruple
LBQS 1429-0053	$14^h32^m29.30^s$	-01°06'16.0"	2.07	?	5.1"	double(?)
SBS 1520+530	$15^h21^m44.83^s$	+52°54'48.6"	1.855	7.1	1.56"	double
HE 2149-2745	$21^h52^m07.44^s$	-27°31'50.2"	2.03	0.5(p)	1.71"	double

For the other nine systems, we took deep and high resolution FORS1 R-band images to exploit wide field images in the analysis of the lensing potential on large scale, performing a galaxy overdensity search and a weak-shear analysis. The near-IR images taken with the ISAAC instrument were mandatory to trace the stellar mass of galaxies at high redshift (z$\sim$3-4), and to measure galaxy photometric redshifts from multi-color analysis. The acquisition and reduction steps can be read in Faure *et al.* (2003, 2004) and in Faure (2004). As much as possible the dataset is completed by HST/WFPC2 and NiCMOS images retrieved from the archives.

3. The lens sample

The goal of this project is to map the line of sight towards a large number of lensed quasars in the southern sky, up to the redshift of the lens. Indeed, the systems studied in this work have never been modeled in a satisfactory manner due to the lack of constraints on the line of sight distribution towards the quasar. In particular, little information is available for characterizing the external shear due to possible intervening galaxy clusters or groups at high redshift along their line of sight.
The quasar coordinates and redshifts, as well as some characteristics of the lensing potential are summarized in Table 1.

4. The method

In this section we describe the method used to search for galaxy clusters/group in the fields 7'×7' around the quasar images. Details about this method are given in Faure *et al.* (2003) for LBQS 1429-0053, Faure *et al.* (2002) for SBS 1520+530 and in Faure *et al.* (2004) for the eight other systems.

For each field we have applied the following procedures to detect possible galaxy groups or clusters:

- **Objects extraction and photometry:**

We used *SExtractor* (Bertin & Arnouts 1996) to extract the objects from the reduced and combined images. The code measures the photometry and the geometry of the objects. We distinguished stars from galaxies using FWHM versus magnitude diagrams and FWHM versus peak surface brightness diagrams.

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Table 2. Value for the Hubble constant obtained considering two models for the lensing potential (raw 2 and 3) towards SBS 1520+530, and computed for the two extreme value of the flux ratio between the quasar images (column 2 and 3).

M_B-M_A	0.83 mag	1.4 mag
L	no good fit	σ_L=228 km s^{-1} r_{cut}=13 kpc
H_0	-	**63±9 km s^{-1} kpc^{-1}**
L+M+C	σ_L=189 km s^{-1} r_{cut}=51 kpc	σ_L=200 km s^{-1} r_{cut}=100 kpc
	σ_M=135 km s^{-1} r_{cut}=20 kpc	σ_M=118 km s^{-1} r_{cut}=40 kpc
	σ_C=718 km s^{-1} r_{cut}=600 kpc	σ_C=400 km s^{-1} r_{cut}=600 kpc
H_0	**52±8 km s^{-1} kpc^{-1}**	**50±8 km s^{-1} kpc^{-1}**

- **Galaxy overdensity search:**

We used two different methods to quantify the galaxy overdensities found in the field around the quasars. First, we compared the galaxy density by magnitude slice in the field around the quasars to the density measured in a reference field (FORS Deep Field, Heidt *et al.* 2003). It provided a measurement of the density deviation in the field.The second way was to cut the images in a grid of 10×10 cells (40" each cell). Most of the cells have the density of a cluster free region. If there was a galaxy cluster/groups in the field, only a few contiguous cells (between four to eight, depending on the redshift of the galaxy cluster/group) would have a relevant galaxy number overdensity.

- **Galaxy photometric redshifts:**

Once a galaxy overdensity was detected, we had to check whether or not it is a bounded structures (or just a galaxy overdensity due to projection effects). For this, we determined the photometric redshifts of the galaxy that built the overdensity. We measured the photometric redshift using the *HyperZ* software (Bolzonella *et al.* 2000).

- **Weak shear analysis and mass reconstruction:**

The weak shear analysis of galaxies located behind the group has been done using the *Im2shape* software (Bridle *et al.* 2002). The distortions and the magnification of the background galaxies allow to measure how massive is the deflector potential. We did this analysis on every fields. It was also possible to derive the mass of the galaxy groups using the *LensEnt* code (Bridle *et al.* 1998, Marshall *et al.* 2002).

For some of this systems we have also done the two last steps:

- **Strong lensing constrains:**

We have deconvolved a small region around the quasar images (20"×20") using the *MCS* code (Magain *et al.* 1998) to identify the position and flux of the quasars, of the main lensing galaxy and of possible secondary lensing galaxies close to the quasar line-of-sight.Indeed accurate measurement of these parameters is necessary to fit the model.

- **Modeling:**

Once all the previous steps have been successfully performed, we were able to fit a model for the total lens, taking into account all the massive structures involved in the deflection potential. For this part of the work we have used the *LensTool* software (Kneib *et al.* 1993).

We have applied this method to the 10 systems of our sample. The main results are given in the following section.

Table 3. Some characteristics of the groups discovered towards the lensed quasars. Column 1: quasar name. Column 2: location of the galaxy group center relative to the quasar brightest image. Column3: photometric redshift of the groups. "?" means that we have not been able to measured it (too few bands).

Quasar	Group location	$z_{phot} \pm \Delta z$
CTQ 414	12" SE	0.5±0.1
HE 0230-2130	38" W	?
LBQS 1009-0252	-	-
B 1030+074	120" SE	?
HE 1104-1805	40" N	2.0±0.1
B 1359+154	7" NE	1.3±0.2
H 1413+117	14" SE	0.8±0.3
HE 2149-2745	7" SE	0.7±0.1

5. Results

5.1. *Results for the first system:SBS 1520+530*

SBS 1520+530 is a doubly imaged quasar at z=1.855 (Chavushyan *et al.* 1997). It has an angular separation of 1.56". The main lensing galaxy at z=0.71 (Burud *et al.* 2002) clearly appeared after deconvolution as well as a secondary lensing galaxy , galaxy M, at 2.5" to quasar image A (Faure *et al.* 2002). A galaxy group was discovered at 1' North-West to the quasar images at $z_{phot}=0.9^{+0.1}_{-0.25}$ (Faure *et al.* 2002). Using the time delay between the quasar images (Δt=130±3 days, Burud *et al.* 2002) we fit two models for the lensing potential. The first model only consider the lensing galaxy L (modeled by a Pseudo Isothermal Elliptical Mass Distribution, PIEMD, Kassiola & Kovner 1993), while the second model consider galaxy L, galaxy M and the galaxy group C (all fitted by a PIEMD). The results for the Hubble constant value are displayed in Table 2.

5.2. *Results for the second system: LBQS 1429-0053*

LBQS 1009-0252-A and -B have a similar spectra at z=2.076. Their separation is 5.1". We took deep optical (FORS1 R-band) and near-IR (ISAAC J and Ks band) images and deconvolved them to look for the lensing galaxy. But this search remained unsuccessful until R=27 mag, J=24 mag and Ks=22.5 mag (Faure *et al.* 2003).We did not find any relevant galaxy overdensity neither any structure more massive than 10^{13} $M_\odot$ in the 7'×7' field around the quasars. Finally, we conclude that we are most probably dealing with a genuine binary quasar rather than with a lensed quasar.

5.3. *Results for the other 8 systems*

Five over the eight studied fields have a galaxy group less massive than 4 $10^{14} M_\odot$ and at a lower redshift than the quasar redshift (see Faure *et al.* 2004). Indeed, in the cas of B 1030+074, the group detected is too far away from the quasar images (2') to play a role in the lensing potential. We have computed the shear that these structures would induce at the quasar images location. In only one case (HE 2149-2745), the shear due to the group could be responsible for the external shear inferred from previous modeling of the lens. This result could meant that in most cases we misunderstand the galaxy lensing potential shape and orientation that dominates the shear strength and orientation. We summarize these results on Table 3.

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6. Conclusion and perspectives

Over the sample of lensed quasar fields studied here, six have a galaxy group. These bounded structures could play a significant role in the total lensing potential and could help, by understanding better the mass distribution inside the Einstein radius, to constrain lensing galaxy dark halo models. Multi-object spectroscopy for next ESO period (PI: C. Faure) will allow to derive the exact redshift of the groups as well as their velocity dispersion, and will allow, finally, to improve the lens models.

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