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Time-Domain Studies of Gravitationally Lensed Quasars

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Abstract. We present an overview and current results of an ongoing optical/NIR monitoring of seven gravitationally-lensed quasars (GLQs) with the 2-m Liverpool Robotic Telescope. The photometric data from the first seven years (2005–2011) of this programme are leading to high-quality light curves, which in turn are being used as key tools for different standard and novel studies. While brightness records of non-lensed distant quasars may contain unrecognized extrinsic variations, one can disentangle intrinsic from extrinsic signals in certain GLQs. Thus, some GLQs in our sample allow us to assess their extrinsic and intrinsic variations; we then discuss the origin of both kinds of fluctuations. We also demonstrate the usefulness of GLQ time-domain data for obtaining successful reverberation maps of the inner regions of accretion disks around distant supermassive black holes, and for estimating the redshifts of distant lensing galaxies.

Keywords. gravitational lensing, black hole physics, accretion, galaxies: general, quasars: general.

An overview of our ongoing Liverpool Quasar Lens Monitoring (LQLM) project is presented in Table 1. The data collection are being carried out in different phases: LQLM I (from 2005 January to 2007 July), LQLM II (from 2008 February to 2010 July) and LQLM III (from 2010 October to the present), and is using available optical/NIR instrumentation. The relevant instruments on the Liverpool Robotic Telescope are the RATCam CCD camera and its associated Sloan *griz* filter set, the RINGO2 optical polarimeter, and the FRODOspec spectrograph (3900–9400 Å). Some astrophysical results and expectations for each target GLQ are given here; a more complete and updated information can be found on the GLENDAMA website http://grupos.unican.es/glendama.

SBS 0909+532. The LQLM I light curves in the r band led to a robust time-delay between its two images of $\Delta t_{AB} = -49 \pm 6$ days and $\Delta t_{ij} = t_j - t_i$, B leading (Goicoechea *et al.* 2008a). In addition, the optical flux ratio A/B changed little in the first 10 years of observations, i.e., between the identification as a quasar pair in 1996 and our LQLM I campaign (see Dai & Kochanek 2009 and references therein). For example, the r-band light curve of the A image and the properly shifted r-band light curve of B were consistent with each other throughout the LQLM I period, so the variability over this time segment was basically intrinsic to the distant quasar (Goicoechea *et al.* 2008a). However, the LQLM III light curves indicate that the r-band flux ratio had evolved in 2010–2011. Gravitational microlensing by stars within the main lensing galaxy could account for the detected extrinsic variation.

FBQ 0951+2635. Gravitational microlensing seems to be an important variability mechanism for this GLQ (Paraficz *et al.* 2006; Shalyapin *et al.* 2009). We are taking a few frames per year in the r band to trace the long-term behaviour of A/B, and thus to

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Table 1. Current status of the LQLM project.

GLQ (redshift)	Comments[1]	Main lens (redshift)	Observation phases[2]	Instruments[2]	Outputs[3] (status)
SBS 0909+532 (z = 1.38)	2 images: A-B size ∼ 1.11″	early-type galaxy (z = 0.83)	I+III	RATCam *gr* filters	LC (final reduction)
FBQ 0951+2635 (z = 1.25)	2 images: A-B size ∼ 1.10″	early-type galaxy (z = 0.26)	I+II+III	RATCam *ri* filters	LC+DI (final reduction)
QSO 0957+561 (z = 1.41)	2 images: A-B size ∼ 6.17″	cD galaxy (z = 0.36)	I+II+III	RATCam *griz* filters FRODOspec RINGO2	LC+S+PM (LC=final reduction, S=first reduction, PM=pending)
SDSS 1001+5027 (z = 1.84)	2 images: A-B size ∼ 2.86″	early-type galaxy (z ∼ 0.2–0.5)	II	RATCam *g* filter	LC (final reduction)
SDSS 1339+1310 (z = 2.24)	2 images: A-B size ∼ 1.69″	early-type galaxy (z ∼ 0.4)	II+III	RATCam *ri* filter	LC+DI (first reduction)
HE 1413+117 (z = 2.56)	4 images: A-D size ∼ 1.35″	? (z = 1.9)	II	RATCam *r* filter	LC+DI (final reduction)
QSO 2237+0305 (z = 1.69)	4 images: A-D size ∼ 1.78″	face-on Sb galaxy (z = 0.04)	II	RATCam *gr* filters	LC (first reduction)

Notes:
[1] See the CASTLES (`http://www.cfa.harvard.edu/castles/`) and SQLS (`http://www-utap.phys.s.u-tokyo.ac.jp/ sdss/sqls/`) websites.
[2] See main text.
[3] LC = light curves, DI = deep images, S = spectra, PM = polarization measurements.

obtain information about the structure of the source and the lensing galaxy (Wambsganss 1990; Kochanek 2004).

QSO 0957+561. We did not find evidence of extrinsic variability in the LQLM I light curves in the g and r bands. These initial brightness records were used to measure time delays between images and optical bands (Shalyapin *et al.* 2008), and to analyse the structure function of the rest-frame UV variability (Goicoechea *et al.* 2008b; Goicoechea *et al.* 2010). Later, LQLM II fluxes in the $griz$ bands, together with concurrent space-based observations from Swift/UVOT and Chandra, unveiled details of the accretion flow and its jet connection in a distant radio-loud quasar for the first time (see Gil-Merino *et al.* 2011). Our global database in the gr bands is also providing surprising results on the chromaticity in Δt_{AB} and the long-term evolution of B/A, which are probably related to the presence of a dense cloud within the cD lensing galaxy along the line of sight to the A image. We are also exploring the spectro-polarimetric evolution of this fascinating first GLQ.

Two new GLQs. SDSS 1001+5027 was discovered in 2005 (Oguri *et al.* 2005). The first monitoring campaign in the R band did not produce any time delay between its two images (Paraficz *et al.* 2009). We have recently observed this double GLQ in the g band (February–May 2010), since we expect to see more variability at shorter wavelengths. If A leads B, and there are no significant extrinsic variations, the LQLM II g-band fluxes suggest a time delay ranging from 12 to 22 days. The other new GLQ (SDSS 1339+1310; Inada *et al.* 2009) was monitored in the r band just after its discovery (February–July 2009; LQLM II). Although Fig. 1 shows prominent flux variations, our LQLM II r-band light curves do not reveal any conclusive delay. Additional data during LQLM III are required in order to decide on the time delay and other properties of this system.

Two famous quads. We followed up the r-band variability of the four images A-D of the Cloverleaf quasar (HE 1413+117) in order to measure its time delays for the first time. The LQLM II fluxes of this GLQ (February–July 2008) enabled us to obtain

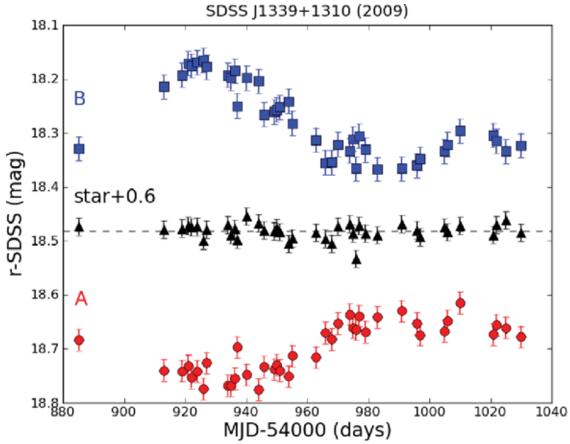

Figure 1. LQLM II r-band light curves of SDSS 1339+1310.

$\Delta t_{AB} = -17 \pm 3$ days, $\Delta t_{AC} = -20 \pm 4$ days and $\Delta t_{AD} = 23 \pm 4$ days (B-C leading, D trailing), which we then used to estimate the redshift of the main lensing galaxies: $z = 1.88^{+0.09}_{-0.11}$ (Goicoechea & Shalyapin 2010). Although useful spectroscopic data are not yet available, we derived an accurate value of z via gravitational lensing. We also monitored the Einstein Cross (QSO 2237+0305) in the g and r bands; the light curves and microlensing analyses will be presented soon. QSO 2237+0305 is the most emblematic target for microlensing studies (Shalyapin *et al.* 2002; Kochanek 2004; Gil-Merino *et al.* 2006).

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