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Multiwavelengths observations of lensed quasars: interband time delays

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Abstract. The time delays between brightness variations in two different optical bands have been measured for a large number of low-redshift AGN and nonlensed quasars. These time delays represent a light travel time between two different emission regions and can be used to test variability mechanisms in the source. We search for the interband delays in a sample of lensed quasars: Q2237+0305, SBS1520+530, HE2149-2745, HE1104-1805, UM673 in the redshift range $1.7 \lesssim z \lesssim 2.7$. From cross-correlation analysis of light curves of the quasars we find that the brightness variations at longer wavelengths may follow the brightness variations at shorter wavelengths. The observed delays are consistent with the delays expected from reprocessing in accretion disc irradiated by the central variable source.

Key words. Quasars: gravitational lensing – Quasars: accretion discs – Quasars: observations

1. Introduction

Active galactic nuclei (AGN) are known to be variable at all wavelengths and on different timescales. The variations in the UV/optical bands are found to be well-correlated implying a common mechanism of variability. The short time delays (of the order of a day) between variations in different bands suggest an external central source of irradiation. The source illuminates the accretion disc producing UV/optical continuum variability. Thus, the UV/optical variations might be driven by reprocessing of the high-energy radiation from the central variable source (Krolik et al. 1991).

The results of the recent simultaneous X-ray/optical monitoring observations of the nearby Seyfert galaxies and low-redshift quasars show that reprocessing might play an important role in AGN variability, although the relation between variations in the X-ray and optical bands can be very complex (Arévalo et al. 2008, 2009; Breedt et al. 2009; Bachev 2009a)). If the reprocessing is a primary mechanism responsible for the UV/optical variability of AGN, the variations at longer wavelengths are expected to lag behind the variations at shorter wavelengths (positive time delay).

The first evidence of such time delays between variations in different optical bands was found in NGC7469. The measured delays showed a wavelength dependence well-

Send offprint requests to: E. Koptelova fitted with $\tau \propto \lambda^{4/3}$. This is in agreement with the prediction from reprocessing in accretion disc with a $T \propto R^{-3/4}$ radial structure (Wanders et al. 1997; Collier et al. 1998). Later, similar time delays were measured in NGC4151 (Oknyanskij et al. 2002). Sergeev et al. (1998) detected interband delays between variations in the optical bands in 14 nearby Seyfert galaxies. The interband correlations between variations in the optical bands were studied in a sample of quasars ($0.2 < z < 2.8$) from the MACHO database (Magdis & Papadakis 2006) and in a sample of low-redshift quasars ($z < 1$), optically monitored at Wise Observatory (Bachev 2009). Although, the wavelength intervals between optical bands were small, some of the quasars showed possible time delays with the variations at bluer wavelengths leading the variations at redder wavelengths. The multiwavelength observations of the lensed quasars can help us to explore the mechanisms of quasar variability at higher redshifts ($z > 1$). The images of the lensed quasars change their brightnesses with time as a result of intrinsic quasar variability, and due to microlensing by the stars in the lensing galaxy. In the first case, the light curves of the multiple quasar images should be similar to each other, apart from a magnitude offset and a lensing time delay. The brightness changes due to microlensing occur independently in each quasar image and given that the lensing time delay is known, it is possible to distinguish between these two causes of brightness variations. Refsdal (1964) showed that the time delay between brightness variations in the quasar images, connected with the quasar variability, can give us an estimate of the Hubble constant. Hence, the main goal of the ongoing monitoring observations of the lensed quasars in the optical/IR bands is to measure the lensing time delays. Much less attention is paid to the analysis of the interband correlations and investigation of the origin of the observed variability. The first interband time delay in the lensed quasar Q0957+561 detected between brightness variations in the g and r bands (Collier 2001), was found to be consistent with the delay expected from the reprocessing in irradiated accretion disc. The new g and r-band observations confirm the existence of the delay (Shalyapin et al. 2008). The evidence of a time delay between brightness variations in the V and R bands has also been found in the lensed quasar Q2237+0305 (Koptelova et al. 2006).

In the present study, we explore the possible interband delays in a sample of lensed quasars monitored in two or more optical bands.

2. Light curve analysis

In order to measure the time delays we perform a cross-correlation analysis of the multiwavelength light curves. There are two methods which are usually used for the cross-correlation analysis of irregularly sampled data: the method of cross-correlation function (CCF) (Gaskell & Peterson 1987) and the method of discrete cross-correlation function (DCF) (Edelson & Krolik 1988). The CCF method is based on a linear interpolation in one of time series. In this method each observed point in one time series is correlated with an interpolated point shifted by time lag τ in another time series. The ends of the both time series are extended by a constant level equal to the last points. In the DCF method, instead of interpolation, the cross-correlation function at a time delay τ is calculated using real data points which are separated by the time τ. In the method the correlation coefficients are averaged for a certain temporal bin size centered on the time delay.

In our study we use a modified version of the CCF method proposed by Oknyanskij (1993). This version has been previously used for the cross-correlation analysis of the NGC4151 multiwavelength light curves (Oknyanskij et al. 2002). In the method, interpolation errors are reduced by imposing a special restriction on the use of interpolated data: only those interpolated points that are separated from the nearest observed points by no more than some fixed value, called interval of interpolation, are used for calculation of the cross-correlation coefficients. The value of interpolation interval is chosen so as to provide the compromise between the desire to decrease the interpolation errors and to increase the resolution of the method. In order to calculate uncertainties in the time delay estimates we use the Flux Randomisation and Random Subset Selection (FR/RSS) method of Peterson et al. (1998).

Q2237+0305. The quadruple lensed quasar Q2237+0305 discovered by Huchra et al. (1985) is an extensively monitored by many groups lensed system. The brightness variations seen in the light curves of four images of Q2237+0305 are mainly due to microlensing by the stars in the lensing galaxy. The variations intrinsic to the quasar are a rather rare phenomenon for this system. The predicted lensing time delays between quasar images are very short, of the order of a day (see e.g. Wambsganss & Paczynski (1994); Schmidt, Webster, & Lewis (1998); Dai et al. (2003)). Thus the quasar's intrinsic variations should show up almost simultaneously in all quasar images.

The first evidence of the simultaneous brightness variations was reported by Østensen et al. (1996). Recently, the quasar's intrinsic variations were observed by the OGLE and Maidanak collaborations in the V and R bands, respectively. The obtained light curves were used to investigate the possibility of measuring the lensing time delays between the images of Q2237+0305 (Vakulik et al. 2006; Koptelova et al. 2006). The analysis of the interband correlations, based on the V and R-band light curves of the images A and C, showed the evidence of a time delay between variations in these two bands with variations in the V band leading the variations in the R band (Koptelova et al. 2006).

In the present study, we analyse the more accurate OGLE V-band light curves and Maidanak R-band light curves of images A and B. In our calculations the lag values range from -100 to 100 days with a step of 0.1 days. The resulting cross-correlation functions calculated between the V and R-band light curves of images A and C are shown in Fig. 1 by a black thick line and by a black thin line, respectively. The time delays corresponding to the peak and local centroids of the cross-correlation functions, and maximum correlation coefficients, $r_{\max}$, are given in Table 1. The errors quoted in the table correspond to the 95 per cent confidence intervals.

SBS1520+530. The double lensed quasar SBS1520+530 (Chavushyan et al. 1997) was monitored at the Nordic Optical Telescope (NOT) in the R band from 1999 to 2001 (Burud et al. 2002), and at Maidanak Observatory in the V and R bands between April 2003 and August 2004 (Gaynullina et al. 2005). The light curves of the quasar images obtained during these monitoring campaigns showed the presence of the brightness variations intrinsic to the quasar. These variations gave an estimate of the lensing time delay in the images of SBS1520+530 (Burud et al. 2002; Gaynullina et al. 2005).

In order to explore the interband correlations, we analyse the Maidanak V and R-band light curves of images A and B of SBS1520+530. During the Maidanak observations the quasar showed low-amplitude ($\Delta m \sim$ 0.1 mag) intrinsic variations. Analysis of the difference light curve (the difference between the light curves of the quasar images after correction for the lensing time delay and magnitude offset) revealed that within statistical uncertainty the two quasar light curves are identical during the time interval covered by the observations. This testifies to absent (or very slow) microlensing variations. If present, the microlensing variations, which are also wavelength-dependent, can be an additional source of noise and might lead to a bias in the time delay estimate.

The results of the cross-correlation analysis, $\tau^{\rm peak}$ and $\tau^{\rm cent}$, are presented in Fig. 1 and summarised in Table 1.

HE2149-2745. The double lensed quasar HE2149-2745 (Wisotzki et al. 1996), was monitored with the 1.5-m Danish Telescope (ESO-La Silla) in the V and Gunn i bands between October 1998 and December 2000. During these observations, the quasar showed slow long-term intrinsic brightness variations (Burud et al. 2002). The external microlensing variations were not reliably detected in the quasar light curves (Burud et al. 2002; Paraficz et al. 2006)

In this study we analyse the V and i-band light curves of image A. The B image light curves are noisier and can not be used for our analysis. The resulting cross-correlation function, shown in Fig. 1 by a black thick line, has a very broad peak with several local maxima. The time delays, corresponding to the peak and centroid of the cross-correlation function, are given in Table 1.

HE1104-1805. The double lensed quasar HE1104-1805 (Wisotzki et al. 1993), was monitored with the 1.3-m SMARTS telescope in the B, R, and J bands between December 2003 and May 2006 (Poindexter et al. 2007). These data were used to improve the previously measured time delay between quasar images. The difference light curves showed the presence of significant microlensing variations in one of the quasar images on the timescale of the lensing time delay (~ 150 days). These microlensing variations may lead to additional uncertainties in our interband time delay analysis.

We analyse the better-sampled B and R-band light curves of image A of HE1104-1805. The resulting cross-correlation function is shown in Fig. 1 by a black thin line. We find that the peak of the cross-correlation function occurs at the time delay $\tau_{\mathrm{A}}^{\mathrm{peak}}=-3.1^{+5.4}_{-8.7}$ days. The corresponding centroid time delay is $\tau_{\mathrm{A}}^{\mathrm{cent}}=-4.3^{+3.1}_{-3.4}$ days. In our analysis the sign of the delay depends on which of the two light curves is chosen for interpolation. Usually, it is the better-sampled light curve. The observed points from the real light curve are then correlated with the points from the interpolated light curve shifted by a time lag. Thus, the sign of the time delay is negative between the interpolated R-band light curve and the observed B-band light curve and vice versa, positive between the interpolated B-band light curve and the observed R-band light curve. The sign "-" here means that the brightness variations in the R-band light curve, chosen for interpolation, follow the brightness variations in the B-band light curve.

UM673 (Q0142-100). The double lensed quasar UM673 (MacAlpine & Feldman 1982) was monitored with the 1.5-m telescope at Maidanak Observatory in the V, R and I bands between August 2003 and November 2005. During the observations, the quasar showed the intrinsic brightness variations seen in both images of UM673 (Koptelova et al. 2009).

Here, we analyse the V and I-band light curves of images A and B. The resulting cross-correlation functions are shown in Fig. 1. The peak and centroid time delays are given in Table 1.

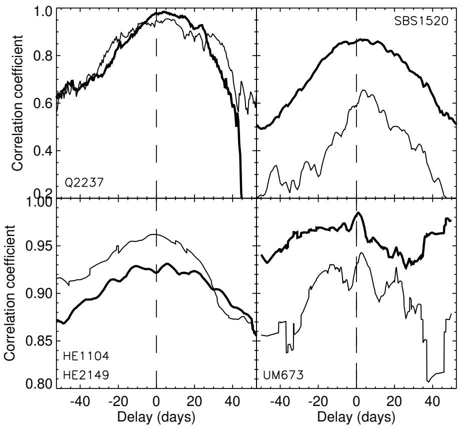

Fig. 1. Cross-correlation functions calculated between the V and R-band light curves of images A (black thick line) and C (black thin line) of the lensed quasar Q2237+0305; between the V and R-band light curves of images A (black thick line) and B (black thin line) of the lensed quasar SBS1520+530; between the V and i-band light curves of image A of the lensed quasar HE2149-2745 (black thick line); between the B and R-band light curves of image A of the lensed quasar HE1104-1805 (black thin line); between the V and I-band light curves of images A (black thick line) and B (black thin line) of the lensed quasar UM673. The vertical dashed lines correspond to zero time delay.

3. Discussion and conclusions

The interband time delays measured for a large number of low-redshift AGN and quasars have been used to test the thermal reprocessing model which predicts the wavelength-dependent time delays between brightness variations in different bands (see e.g. Collier (2001); Sergeev et al. (1998)).

Table 1. Interband time delays obtained from the cross-correlation analysis of the lensed quasar light curves in comparison with the delays expected from reprocessing $\tau_{\rm irr}^{\rm model}$ and intrinsic emission due to viscous heating $\tau_{\rm vis}^{\rm model}$ in the standard accretion disc.

Object	z	Bands	$\tau^{\rm peak}$ (days)	$\tau^{\rm cent}$ (days)	$r_{\max}$	$\tau_{\rm irr}^{\rm model}$ (days)	$\tau_{\rm vis}^{\rm model}$ (days)
Q0957+561 Collier (2001)	1.41	*gr*				3.4	12.5
AB			$4.1^{+0.9}_{-4.1}$	$3.4^{+1.5}_{-1.4}$			
Q2237+0305	1.69	*VR*				1.1	1.4 ÷ 4.7
A			$5.1^{+0.4}_{-2.9}$	$5.6^{+0.7}_{-0.9}$	0.98		
C			$5.2^{+2.9}_{-11.5}$	$5.1^{+0.7}_{-4.5}$	0.95		
SBS1520+530	1.86	*VR*				0.8	2.6
A			$4.4^{+2.4}_{-9.5}$	$2.3^{+2.5}_{-2.5}$	0.87		
B			$6.1^{+2.2}_{-6.7}$	$2.8^{+3.7}_{-2.3}$	0.66		
HE2149-2745	2.03	*Vi*				1.0	22.8
A			$4.0^{+10.0}_{-13.0}$	$2.5^{+4.8}_{-6.3}$	0.93		
HE1104-1805	2.32	*BR*				3.3	15.5
A			$3.1^{+5.4}_{-8.7}$	$4.3^{+3.1}_{-3.4}$	0.97		
UM673	2.72	*VI*				10.7	16.9
A			$1.2^{+2.3}_{-11.4}$	$0.8^{+5.8}_{-4.4}$	0.98		
B			$2.9^{+3.9}_{-8.1}$	$3.1^{+1.8}_{-3.5}$	0.94		

In the present study, we search for the interband time delays in the lensed quasars Q2237+0305, SBS1520+530, HE2149-2745, HE1104-1805 and UM673. These time delays allow us to test the quasar variability mechanisms in the redshift range $1.7 \lesssim z \lesssim 2.7$. In Table 1 we summarise the obtained results. The time delays were estimated using the peak, $\tau^{\rm peak}$, and centroid, $\tau^{\rm cent}$, of the cross-correlation function. In all cases, we find that the brightness variations at longer wavelengths may follow the brightness variations at shorter wavelengths by a few days in the observer rest frame. The 95 per cent confidence intervals quoted are large and the detected time delays need further confirmation.

In order to compare the observed delays with the delays that might be expected from reprocessing in accretion disc, we consider a model of the standard accretion disc irradiated by the central variable source of the X-ray emission (Collier et al. 1998; Cackett et al. 2007). This model accounts both for intrinsic emission from the accretion disc and reprocessing of the X-ray emission. The expected time delays $\tau_{\rm irr}^{\rm model}$ are given in the seventh column of Table 1. In the last column of Table 1 we also present the time delays $\tau_{\rm vis}^{\rm model}$ expected under the assumption that the emission from the accretion disc is mainly due to the viscous heating. These time delays were calculated using the published estimates of the black hole masses and mass accretion rates (Peng et al. 2006; Kochanek 2004). The expected time delays $\tau_{\rm vis}^{\rm model}$ are generally longer than the observed ones. Thus, we find that the observed time delays are rather consistent with the scenario where reprocessing of the X-rays is a primary mechanism of quasar variability, at least on the timescales investigated by us.

In our study we explore the interband time delays in the quasars from the redshift range $1.7 < z < 2.7$. The sampling analysed is small and the delays found should be confirmed by future observations. The new multiwavelength observational data for a larger number of AGN and quasars, both at low and high redshifts, will help us to understand connections between different emission regions of the accretion disc and the origin of variability in AGN and quasars.

4. DISCUSSION

BIDZINA KAPANADZE: You have mentioned that Sergeev et al. (2005) performed the investigation of interband delays for 14 AGNs. Were the blazars among them too?

EKATERINA KOPTELOVA: They studied the light curves of nearby Seyfert galaxies, observed in 4 optical bands.

BOZENA CZERNY: Have you checked the possibility of the reverse of time delay direction? Such delays are consistent with viscous propagation of signal inwards.

EKATERINA KOPTELOVA: We do not find the evidence of the reverse time delays at least on the timescales that we analyse. The time scales of variations associated with the viscous propagation of the signal might be long for high-redshift quasars. Thus, the observations should cover longer time intervals than we consider in our analysis.

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