PG 1115+080: NEW ANALYSIS OF LIGHT CURVES CONFIRMS OLD TIME DELAY RESULTS

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ABSTRACT. We analyze all publicly available long-term optical observations of the gravitationally lensed quasar PG1115+080 with the aim of measuring time delays between its four components. In particular, we present analysis of the Maidanak light curves of the PG1115+080 components obtained between 2001 and 2006 (Tsvetkova et al. 2010). We find that the light curves of the 2006 observational season show almost linear trend with some fast variations seen only in the A1 and C components. This can be as due to microlensing or observational errors. These fast variations can decrease statistical significance of the time delay estimates or even produce misleading results. Application of the MCCF technique (Oknyanskij 1993) to photometric data collected in the 2004-2005 seasons gives time delay values t_{BC} = 22±3, t_{AC} = 12±3, and t_{BA} = 10±3 days, which are in agreement with previous results of Schechter et al. (1997) and Barkana (1997) reported for the 1995-1996 light curves analyzed using two different statistical methods. The ratio t_{AC}/t_{BA} between our intermediate delays is about 1.2 that is close to the value reported by Barkana (~1.13) and predicted by lens models (~1.4) unlike the Schechter's and Vakulik's (2009) values (~ 0.7 and ~2.7).

Time delays between quasar's intrinsic brightness variations seen in different images of gravitationally lensed quasars provide a tool for an optical measurement of the Hubble constant H_0 (Refsdal 1964). The difficulties of the H_0 measurement based on the lensed quasars time delays were broadly discussed. The main one is the model of the lensing galaxy. The values of H_0 from lensing time delays are generally less than the most recent estimate of $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1} obtained in the HST Key Project with the use of Cepheids (Freedman et al. 2001).

The PG 1115+080 is the first quadruple gravitationally lensed quasar, which was initially discovered as a triplet (Weymann et al. 1980, Hege et al. 1981). The system was claimed to be a promising candidate for an optical measurement of the Hubble constant through a time delay estimation. Multiple time delays were published for that system by Schechter et al. in 1997 based on optical observations conducted in 1995-1996 with four instruments. They found that the component C leads the component B by 23.7±3.4 days and components A_1 and A_2 by 9.4±3.4 days. The same data were analyzed by Barkana with different statistical technique that provides the time delay values $t_{CB} = 25.0^{+3.3}_{-3.8}$ days and $t_{CA} = 13.4^{+2.0}_{-2.2}$ days. New time delay estimates for PG1115 were published in 2010 when data of monitoring campaign conducted at Maidanak Observatory (Uzbekistan) were analyzed by Tsvetkova et al. (2010). The authors applied their own method and obtained results that considerably differ from values, determined earlier by Schechter et al. and Barkana, and result in larger values of the Hubble constant.

We analyzed observations of PG 1115+080 conducted with 1.5 m telescope at Maidanak observatory in 2001-2006 (Tsvetkova et al. 2010) and R-band observations of the quasar with SMARTS 1.3 m telescope at CTIO and 2.4 m telescope at the MDM Observatory in 2004-2006 (Morgan et al. 2008). The light curves of PG1115+080 are presented in Figure 1. The time delay between A1 and A2 is expected to be hours, so we averaged light curves of the A1 and A2 components to compose the A light curve. The Maidanak observations is the most complete and homogeneous data of the long-term monitoring of the PG1115 available. However, we have found that A1, A2, B, C light curves for 2006 represent almost linear trend with some fast variations only in A1 and C components that can be due to microlensing or observational errors. We believe that those data can decrease the statistical significance of time delay estimates or even provide misleading results (see Figure 2), so we excluded it from the time delay analysis. An idea to combine Maidanak data with the SMARTS photometry published by Morgan et al. (2008) seemed quite appealing. But large scatter of the data points in B and C light curves hamper detection of the quasar brightness variations as was noted by Vakulik et al. (2009), so we used SMARTS data only for A1+A2. Then we applied the modified cross-correlation function (MCCF) technique (Oknyanskij 1993, Koptelova et al. 2006) to the PG1115 light curves. We calculated cross-correlation functions for observational seasons 2004, 2005, 2006 separately, and for the combined seasons 2004-2006 and 2004-2005. Cross-correlation functions for the CB pair of PG1115+080 components calculated for 2004, 2005 and 2004-2005 data are presented in Figure 2 (left). The cross-correlation function for the CB pair in 2006 is presented in Figure 2 (right). It has several maxima and is unstable. We also have found that data from 2006 makes the result for the combined season 2004-2006 unstable. So we decided to rely only on 2004-2005 data to estimate the time delays. Figure 3 shows cross-correlation functions for the CB pair based on Schechter data (left) and for the AB and AC pairs of PG1115+080 components based on SMARTS (Morgan et al. 2008) and Maidanak (Tsvetkova et al. 2010) observations (right). We find that component C leads component B by 22±3 days and components A1 and A2 by 12±3 days, and component A leads component B by 10±3 days. The time delay results for PG1115+080 are summarized in Table 1.

Table 1. PG1115+080 time delays

	t_{BA}, days	t_{AC}, days	t_{BC}, days	t_{AC}/t_{BA}
Schechter et. al. 1997	14.3	9.4±3.4	23.7±3.4	0.7
Barkana, 1997	$11.7^{+2.9}_{-3.2}$	$13.4^{+2.0}_{-2.2}$	$25.0^{+3.3}_{-3.8}$	1.1
Tsvetkova et. al. 2010	$4.4^{+3.2}_{-2.5}$	$12.0^{+2.5}_{-2.0}$	$16.4^{+3.5}_{-2.5}$	2.7
This work	10±3	12±3	22±3	1.2

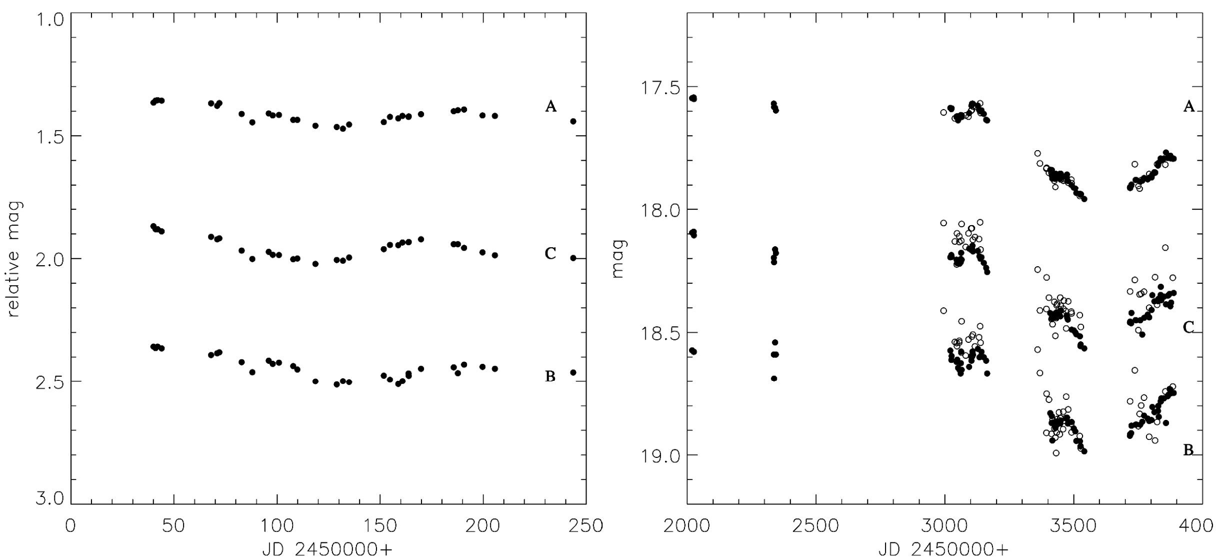

Figure 1. The light curves of PG1115+080 in 1995-1996 (left, A light curve is shifted by 1.5 mag) based on data of Schechter et al. (1997) and combined SMARTS (open circles) and Maidanak (filled circles) light curves of PG1115+080 in 2001-2006 (right, A light curve is shifted by 0.7 mag) based on data of Morgan et al. (2008) and Tsvetkova et al. (2010)

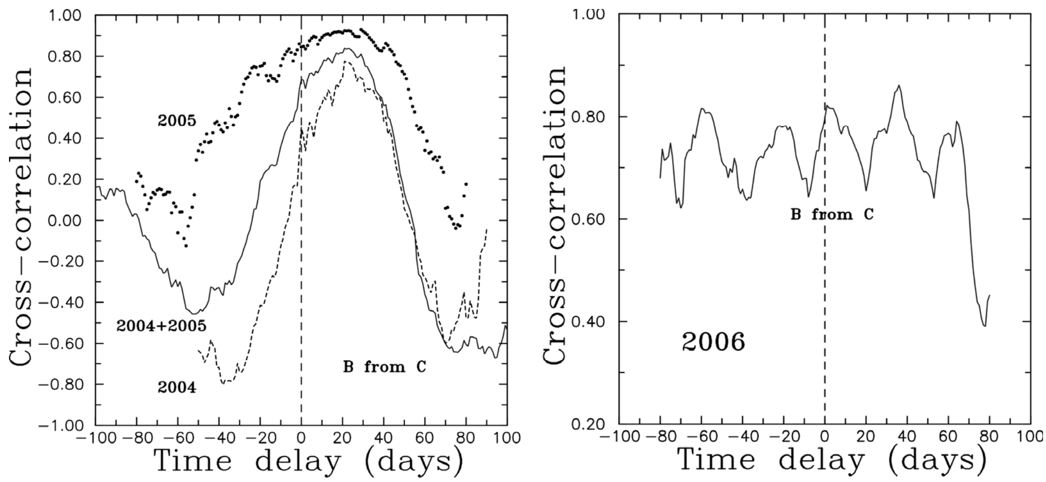

Figure 2. MCCF cross-correlation functions for the CB pair of PG1115+080 components based on Maidanak observations in 2004-2005 (left) and 2006 (right)

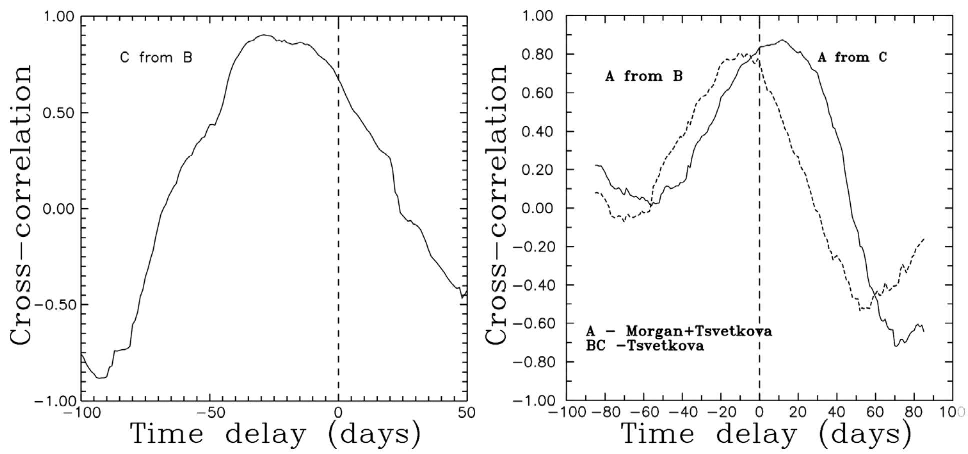

Figure 3. MCCF cross-correlation functions for the CB pair of PG1115+080 components based on Schechter et al. data (left) and for the AB and AC pairs of PG1115 components based on SMARTS and Maidanak observations (right)

Time delays found are in correspondence with the earlier results of Schechter et al., Barkana et al. and partially with the results of Vakulik et al. (2009) within the accuracy of the analysis. Unfortunately, even all available data do not allow to unambiguously and justified vote for larger or smaller value for the BC time delay and consequently for smaller or larger value of the Hubble constant. New observations and, probably, reprocessing of the available data are needed to attain better accuracy. New methods of analysis, taking into account microlensing and weights of all data points, need to be developed.

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