MEASUREMENT OF THE BROAD-LINE REGION SIZE IN A LUMINOUS MACHO QUASAR

Doron Chelouche1, Eliran Daniel2, and Shai Kaspi2,3

1 Department of Physics, Faculty of Natural Sciences, University of Haifa, Haifa 31905, Israel; doron@sci.haifa.ac.il
2 School of Physics & Astronomy and the Wise Observatory, Tel-Aviv University, Tel-Aviv 69978, Israel; shai@wise.tau.ac.il, elirandviv@gmail.com
3 Department of Physics, Technion, Haifa 32000, Israel

Received 2011 December 8; accepted 2012 April 3; published 2012 April 26

ABSTRACT

We measure the broad emission line region (BLR) size of a luminous, \( L \sim 10^{47} \text{erg s}^{-1} \), high-z quasar using broadband photometric reverberation mapping. To this end, we analyze \(~7.5\) years of photometric data for MACHO 13.6805.324 (\( z \simeq 1.72 \)) in the B and R MACHO bands and find a time delay of \( 180 \pm 40 \) days in the rest frame of the object. Given the spectral-variability properties of high-z quasars, we associate this lag with the rest-UV iron emission blends. Our findings are consistent with a simple extrapolation of the BLR size–luminosity relation in local active galactic nuclei to the more luminous, high-z quasar population. Long-term spectroscopic monitoring of MACHO 13.6805.324 may be able to directly measure the line-to-continuum time delay and test our findings.

Key words: galaxies: active – methods: data analysis – quasars: emission lines – quasars: individual (MACHO 13.6805.324) – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

Our understanding of galaxy and black hole (BH) formation and co-evolution has progressed significantly in recent years (Wandel 1999; Ferrarese & Merritt 2000; Haring & Rix 2004; Peng et al. 2006; Bennert et al. 2010; Cisternas et al. 2011) with new observations being able to probe the first epoch of quasar activity, and place interesting constraints on the mechanisms responsible for BH growth and galaxy formation (Hughes & Blandford 2003; Trakhtenbrot et al. 2011). Gaining further physical insight requires that the BH masses be determined with good accuracy in a large sample of objects.

Presently, the best means for weighing BHs in quasars is via the reverberation mapping (RM) technique (Peterson 1993), which measures the size of the broad-line region (BLR). This, combined with a measure of the velocity dispersion of the BLR, can be used to estimate the BH mass (Peterson et al. 2004). To date, BH masses in \(~45\) low-z objects have been measured in this way leading to various scaling laws with other quasar properties. These relations are often extrapolated to high-z objects to allow for the \emph{indirect} estimate of their BH mass (Netzer 2003). Nevertheless, it is not clear that such extrapolations are meaningful, and a more direct measure of the BH mass in such objects is highly desirable.

Here, we report new measurements for the BLR size in a \( z \simeq 1.72 \) luminous quasar, using photometric RM (Chelouche & Daniel 2012), and by analyzing \(~7.5\) years of data from the MACHO survey (Geha et al. 2003). Section 2 presents the analysis and results, with a follow-up discussion in Section 3.

2. ANALYSIS AND RESULTS

To date, some 200 quasars have been confirmed behind the Magellanic clouds (Dobrzycki et al. 2002; Geha et al. 2003; Kozłowski et al. 2012). In the course of analyzing their photometric data, we report our findings for MACHO 13.6805.324, an \( m_R = 18.66 \) quasar at \( z \simeq 1.72 \) having a monochromatic luminosity\(^4\) \( \lambda L_\lambda(1350 \text{Å}) \sim 3 \times 10^{46} \text{erg s}^{-1} \). We focus on this object as it has the best-sampled \( B \) and \( R \) light curves, as well as the highest fractional variability (Kaspi et al. 2007 and references therein), \( F_{\text{var}} \simeq 0.16 \), of a high-z quasar in the Geha et al. (2003) sample. This object is consistent with being radio-quiet down to a flux limit of \(~6\) mJy (5 mJy) at 21 cm (13 cm) (Marx et al. 1997; Mauch et al. 2003). A more complete analysis of the MACHO quasar sample is deferred to a forthcoming publication.

We choose to work with the original MACHO bandpasses rather than transform into standard \( B \) and \( R \) bands. This reduces the spectral overlap as the photometric transformations require linear combinations of the MACHO magnitudes. Light curves were filtered against poor data: all points with errors larger than \( \xi \) times the mean error or those which deviate from the light curve mean by more than \( \xi \) standard deviations were discarded (Figure 1).

2.1. Spectral Decomposition

To effectively use the photometric RM technique of Chelouche & Daniel (2012), it is helpful to identify the band with the larger contribution of emission lines to its variance. If the emission line contribution to the flux may be used as a proxy to its variable component (e.g., as would be the case if

\(^4\) To estimate the monochromatic luminosity of MACHO 13.6805.324 at 1350 Å, we take the reported \( R \)-magnitudes from Geha et al. (2003), employ a standard \( K \)-correction, and account for the extinction behind the LMC using the results of Zaritsky et al. (2004, see: http://ngala.as.arizona.edu/dennis/lmcext.html). To this end, we average over 50 stars of all types in the direction of the quasar and identify the upper turnover in the extinction distribution, at \( A_V \simeq 1.3 \) mag, with the effective extinction of the background source. We conservatively estimate the uncertainty on the luminosity to be a factor three, to account for the potentially patchy structure of LMC disk. Our estimate is consistent with \( m_{B-R} \) for MACHO 13.6805.324 being larger by \(~0.67\) mag than typical, as concluded by integrating the Vanden Berk et al. (2001) composite quasar spectrum over the MACHO bands, and assuming a Galactic extinction law. Using concordance (0.3, 0.7, 0.3) cosmology, we find \( \lambda L_\lambda(1350 \text{Å}) \sim 3 \times 10^{46} \text{erg s}^{-1} \).
the relative flux variations in all emission lines were similar; see Section 3), then by spectral decomposition and knowledge of the instrumental throughput, one can identify the line-rich and line-poor bands. Unfortunately, the quality of available spectra of MACHO 13.6805.324 is low and the data are not flux calibrated. Nevertheless, their broad consistency with the composite quasar spectrum of Vanden Berk et al. (2001, see Figure 2) motivated us to use the latter for our purpose.

Prominent emission lines at $z = 1.72$ include the C iv $\lambda 1548$, Mg ii $\lambda 2799$, as well as the iron complexes (Figure 2). To account for the iron-blend contribution to the spectrum, we use the iron template of Vestergaard & Wilkes (2001). An underlying power-law continuum model was assumed, $F_\lambda \propto \lambda^{-1.63}$, which is somewhat different from the one used by Vanden Berk et al. (2001), and better accounts for the flux level at $\sim 6000$ Å (observed), where little iron blend and Balmer continuum emission is present. Emission lines and blends were individually convolved with a single Gaussian kernel of some amplitude and width, and a qualitative agreement was sought with the Vanden Berk et al. (2001) composite spectrum (Figure 2). The solution is neither strictly unique, nor very physical, and its sole purpose is to qualitatively assess the relative contribution of the various emission components to the broadband flux.

Weighing the decomposed spectrum by the instrumental throughput (Alcock et al. 1999), we find that the $R$ band has the greater relative contribution of emission lines to its flux. Specifically, the iron emission blends contribute a net of $\sim 10\%$ to the flux in the bands, with the relative contribution of the Mg ii $\lambda 2799$ and C iv $\lambda 1548$ to their respective bands being $\geq 4$ times smaller.

### 2.2. Uncovering the Time Lag

Having identified the line-rich band, we now proceed to measure the line-to-continuum time delay. Following Chelouche & Daniel (2012), we compute two statistical estimators for the line-to-continuum cross-correlation function:

$$\xi_{CA}(\delta t) = f_R \ast f_B - f_B \ast f_B,$$

and

$$\xi_{AA}(\delta t) = f_R \ast f_R - f_B \ast f_B$$

(“$\ast$” denotes convolution and $f_B$, $f_R$ are the light curves in the $B$ and $R$ bands, respectively; see Figure 3). With these definitions, a peak at $\delta t > 0$ indicates an emission component in the $R$ band, which lags behind the $B$ band. To calculate these statistical estimators, we use two independent schemes: the interpolated cross-correlation function (ICCF; Peterson et al. 2004) and the $z$-transformed discrete correlation function (ZDCF; Alexander 1997). The former has the advantage of being somewhat more sensitive, while the latter is less affected by sampling.

Results for $\xi_{CA}$ and $\xi_{AA}$ using the ICCF and ZDCF schemes, and for two levels of light curve filtering, are presented in Figure 3. All analyses give consistent results: $\xi_{CA}$ and $\xi_{AA}$ peak at $\delta t \sim 400$–600 days. Unsurprisingly, the peak is more significant when modest filtering ($\zeta = 2$) is applied, resulting in $\xi_{CA}$, $\xi_{AA}$ being significant at the $\sim 2.8\sigma$, $5\sigma$ ($\sigma$ is the standard deviation) level, respectively.

To verify that the observed signal is indeed associated with a lagging component in the $R$ band, we reversed our choice of line-rich and line-poor bands, and repeated the analysis: no significant peak was detected at $\delta t > 0$ (instead, a highly significant trough was detected at $\delta t \sim 400$–600 days; not shown). In addition, we carried out sets of Monte Carlo simulations (Chelouche & Daniel 2012) wherein the $B$-band light curve was convolved with a Gaussian kernel having prescribed time delay and width (the latter was taken to be half of the former but the results are not very sensitive to the particular kernel chosen). The resulting light curve was then scaled down and added to the $B$-band signal so that the line contribution to the flux is $\sim 10\%$. The combined light curve was then sampled with the cadence of the $R$ band to create a
Synthetic light curve, $f_R^B$. The $\xi$-estimators were calculated for the light curve pair $[f_B^R, f_B^A]$, and the results for several input time lags are shown in Figure 3. Clearly, the observed signal is qualitatively reproduced by our simulations for lags of the order of 400 days. This (1) confirms that the observed signal is indeed associated with a lagging emission component in the $R$ band and is not spurious and (2) that the time-lag constraints deduced below are meaningful and are not significantly biased.

We estimate the time lag and its uncertainty in the following way: the peak in $\xi_{CA}$ and $\xi_{AA}$ is identified with the time lag for each Monte Carlo realization (a total of 100 realizations are used for each numerical scheme). A time-lag distribution is then obtained whose mean is identified with the time lag and its uncertainty with the standard deviation. We find that the time lag is $480 \pm 100/530 \pm 70$ days (ZDCF) or $490 \pm 80/490 \pm 50$ days (ICCF) for the $\xi_{CA}/\xi_{AA}$ statistical estimator. We conservatively estimate the lag to be $500 \pm 100$ days, which corresponds to a rest-frame lag, $\tau \approx 180 \pm 40$ days.

3. DISCUSSION AND CONCLUSIONS

With only photometric data at hand, interpreting our findings is not straightforward: while we have a statistically robust time-lag measurement, it is difficult to associate it with a specific emission line.5 That being said, it is very likely that the observed time lag is associated with the iron emission blends for the following reasons: (1) a positive peak in $\xi_{CA}, \xi_{AA}$ indicates that emission lines contributing to the $R$ band are responsible for the signal, (2) the iron contribution to the $R$ band typically exceeds that of the Mg II 2799 Å line by a factor $\gg 4$ (Figure 2), and (3) the implied flux variation of the iron blend is consistent with that seen in low-$z$ objects (Maoz et al. 1993; Vestergaard & Peterson 2005) and indirectly deduced for high-$z$ quasars (Meusinger et al. 2011).6

Little is known with confidence about the physical properties of the UV iron-emitting region, and a statistically significant time lag, reflecting on its size, exists for only one additional low-luminosity source, NGC 5548 (Maoz et al. 1993). Taken together, the results imply that the size–luminosity scaling for this region is consistent with that of other broad lines (Kaspi et al. 2005, 2007; see our Figure 5). Interestingly, the inferred sizes of the iron- and C IV $\lambda 1549$-emitting regions are comparable in NGC 5548 (Maoz et al. 1993). If also true for MACHO 13.6805.324 then we find consistency with a simple extrapolation of size–luminosity relation for the C IV-emitting region, as obtained for lower luminosity sources, to the more luminous quasar population (Figure 5). A meaningful comparison with the size–luminosity relations

Figure 2. Quasar composite spectrum at $z = 1.72$ (Vanden Berk et al. 2001) overlaid with the throughput curves of the MACHO $B$- and $R$-filters (the somewhat erratic behavior is real and results from an interference pattern; C. Stubbs 2011, private communication). A qualitative spectral decomposition into the prominent emission components is shown including the iron blend (gray curve), the C IV $\lambda 1909$, and Mg II $\lambda 2799$ lines (magenta curves), and a power-law continuum (dashed line). Designated minor emission lines were also included in the spectral decomposition (green curve). Integrating over the emission line flux, and taking into account the wavelength-dependent throughput, the largest contribution to line emission is from the iron complexes in the $R$ band. The contribution of the C IV and the Mg II lines is roughly four times smaller than iron’s and their relative contribution to their respective bands is similar. Also shown are the two (non flux-calibrated, slightly shifted in wavelength range for clarity) optical spectra for MACHO 13.6805.324, which were multiplied by a power-law function of wavelength so that their trend roughly

5 Another possibility is that the signal originates in an unidentified continuum emission component. While this cannot be excluded based on available data, we find it rather unlikely given that continuum emission, by definition, extends over a broad wavelength range, and the fact that there is no clear reason why the lag should be similar to that which characterizes emission lines.

6 In a recent work, Meusinger et al. (2011) analyzed Stripe 82 SDSS quasars and found that the combined flux from all emission lines and blends varies by $\sim 10\%$, which is consistent with the relative variations measured for individual lines by Kaspi et al. (2007). This implies that similar flux variations of the iron blend are characteristic of quasars (see also Wilhite et al. 2005 for some additional constraints on the time variability of emission lines in high-$z$ quasars).
Shaded regions indicate the uncertainty. The ZDCF calculations are shown as points with error bars in dotted lines. Blue (red) colors correspond to agreement with a time lag of \( \zeta = 2 \) (left) and \( \zeta = 10 \) (right).

There are uncertainties associated with the use of carbon lines for measuring the black hole mass. For other rest-UV lines, the uncertainty is currently limited by small number statistics.

The size of the line-emitting region is known; an excess power is seen at around 500 days in the cross-correlation signal compared to the autocorrelation signal (thick lines). The simulated signal qualitatively reproduces the excess power in the cross-correlation term, at the right timescales, for three input time lags (see the text and legend).

The BH mass may be determined via statistics. For other rest-UV lines, the uncertainty is currently limited by small number statistics.

The BH mass may be determined via statistics.

Figure 3. Photometric RM analysis. Top panel: an excess power is seen at around 500 days in the cross-correlation signal compared to the autocorrelation signal (thick lines). The simulated signal qualitatively reproduces the excess power in the cross-correlation term, at the right timescales, for three input time lags (see the text and legend).

The BH mass may be determined via statistics.

The BH mass may be determined via statistics.

The BH mass may be determined via statistics.

The BH mass may be determined via statistics.

The BH mass may be determined via statistics.
Figure 4. Arbitrarily normalized (non flux-calibrated) spectra of MACHO 13.6805.324 (Geha et al. 2003; S. Kozłowski 2011, private communication; see legend) show two prominent emission lines. A cubic spline was fit far from the prominent line locations to normalize the spectrum (not shown), and single Gaussian models were overlaid to constrain the FWHM range, as indicated by the shaded areas. Only the red wing of the C iv λ1549 line was used for fitting purposes due to potential absorption features just blueward of its peak (left panel). Similarly, only the red wing of the C iii λ1909 line was used for FWHM estimation to avoid blending with other emission lines just blueward of its center (right panel). We note that FWHM measurements for this line should be treated with caution since iron blend emission may be substantial (see also Figure 2), and is difficult to estimate given the poor S/N of the non flux-calibrated data.

(A color version of this figure is available in the online journal.)

Figure 5. BLR size–luminosity relation (left; adopted from Kaspi et al. 2007; see their paper for a discussion of the various fitted relations) and the mass–luminosity relation (right; adopted from Peterson et al. 2004, and augmented by up-to-date data from Peterson et al. 2005, Denney et al. 2006, Kaspi et al. 2007, Grier et al. 2008, Bentz et al. 2009, Denney et al. 2010, and Grier et al. 2012 using the composite spectrum of Vanden Berk et al. 2001 to convert monochromatic luminosities to λL(1350 Å); uncertainties are not shown). Left: plotted are data from Peterson et al. (2004, 2005) and Kaspi et al. (2005, 2007) as well as our results for MACHO 13.6805.324, which are in agreement with both relations. Also shown, for comparison, are reliable BLR size measurements for the iron blend (Maoz et al. 1993) and the C iii λ1909 and Mg ii λ2799 emission lines (Metzroth et al. 2006); see legend. Evidently, the BLR size measured here lies on the extrapolation of the R–L relation, as obtained for low luminosity, low-z objects. Right: interestingly, MACHO 13.6805.324 is consistent with emitting at ≳10% of its Eddington rate, in agreement with the efficiency of other bright quasars (note that the mass reported here for S5 0836+71 is ∼1.8 times larger than the value reported in Kaspi et al. 2007 and follows from the normalization of Onken et al. 2004). Curves of constant L/L Edd are also plotted (dashed lines) assuming the bolometric correction used by Kaspi et al. (2007).

(A color version of this figure is available in the online journal.)

We are grateful to Marla Geha for providing us with the MACHO quasar light curves and spectra in electronic form, and for commenting on an earlier version of this Letter. We thank S. Kozłowski for providing us with a recently acquired spectrum of MACHO 13.6805.324, and M. Vestergaard for supplying us with iron emission templates in electronic form. Fruitful discussions
with H. Netzer and O. Shemmer are greatly appreciated, as well as helpful comments by the referee. This research has been supported in part by an FP7/IRG PIRG-GA-2009-256434 grant as well as by grant 927/11 from the Israeli Science Foundation.

REFERENCES

Alcock, C., Allsman, R. A., Alves, D. R., et al. 1999, PASP, 111, 1539
Alexander, T. 1997, Astron. Time Ser., 218, 163
Baskin, A., & Laor, A. 2005, MNRAS, 356, 1029
Bennert, V. N., Treu, T., Woo, J.-H., et al. 2010, ApJ, 708, 1507
Bentz, M. C., Peterson, B. M., Netzer, H., Pogge, R. W., & Vestergaard, M. 2009, ApJ, 697, 160
Cisternas, M., Jahnke, K., Inskip, K. J., et al. 2011, ApJ, 726, 57
Chelouche, D., & Daniel, E. 2012, ApJ, 747, 62
Denney, K. D., Bentz, M. C., Peterson, B. M., et al. 2006, ApJ, 653, 152
Denney, K. D., Peterson, B. M., Pogge, R. W., et al. 2010, ApJ, 721, 715
Dobrzycki, A., Groot, P. J., Macri, L. M., & Stanek, K. Z. 2002, ApJ, 569, L15
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Geha, M., Alcock, C., Allsman, R. A., et al. 2003, AJ, 125, 1
Grier, C. J., Peterson, B. M., Bentz, M. C., et al. 2008, ApJ, 688, 837
Grier, C. J., Peterson, B. M., Pogge, R. W., et al. 2012, ApJ, 744, L4
Haring, N., & Rix, H.-W. 2004, ApJ, 604, L89
Hu, C., Wang, J.-M., Ho, L. C., et al. 2008, ApJ, 687, 78
Hughes, S. A., & Blandford, R. D. 2003, ApJ, 585, L101
Kaspi, S., Brandt, W. N., Maoz, D., et al. 2007, ApJ, 659, 997
Kaspi, S., Maoz, D., Netzer, H., et al. 2005, ApJ, 629, 61
Kaspi, S., Smith, P. S., Netzer, H., et al. 2000, ApJ, 533, 631
Kozlowski, S., Kochanek, C. S., Jacyszyn, A. M., et al. 2012, ApJ, 746, 27
Maor, D., Netzer, H., Peterson, B. M., et al. 1993, ApJ, 404, 576
Marx, M., Dickey, J. M., & Mebold, U. 1997, AA, 126, 325
Mauch, T., Murphy, T., Buttery, H. J., et al. 2003, MNRAS, 342, 1117
Metzroth, K. G., Onken, C. A., & Peterson, B. M. 2006, ApJ, 647, 901
Meusinger, H., Hinz, A., & de Hoon, A. 2011, A&A, 525, A37
Netzer, H. 2003, ApJ, 583, L5
Onken, C. A., Ferrarese, L., Merritt, D., et al. 2004, ApJ, 615, 645
Peng, C. Y., Impey, C. D., Ho, L. C., Barton, E. J., & Rix, H.-W. 2006, ApJ, 640, 114
Peterson, B. M. 1993, PASP, 105, 247
Peterson, B. M. 1994, in ASP Conf. Ser. 69, Reverberation Mapping of the Broad-Line Region in Active Galactic Nuclei, ed. P. M. Gondhalekar, K. Home, & B. M. Peterson (San Francisco, CA: ASP), 1
Peterson, B. M., Bentz, M. C., Desroches, L.-B., et al. 2005, ApJ, 632, 799
Peterson, B. M., Ferrarese, L., Gilbert, K. M., et al. 2004, ApJ, 613, 682
Shemmer, O., Brandt, W. N., Netzer, H., Maiolino, R., & Kaspi, S. 2006, ApJ, 646, L29
Trakhtenbrot, B., Netzer, H., Lira, P., & Shemmer, O. 2011, ApJ, 730, 7
Vanden Berk, D. E., Richards, G. T., Bauer, A., et al. 2001, AJ, 122, 549
Vestergaard, M., & Peterson, B. M. 2005, ApJ, 625, 688
Vestergaard, M., & Wilkes, B. J. 2001, AJ, 135, 134
Wandel, A. 1999, ApJ, 519, L39
Wilhithe, B. C., Vanden Berk, D. E., Kron, R. G., et al. 2005, ApJ, 633, 638
Zaritsky, D., Harris, J., Thompson, I. B., & Grebel, E. K. 2004, AJ, 128, 1606