Continuum reverberation mapping in a $z = 1.41$ radio-loud quasar

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Abstract. Q0957+561 was the first discovered gravitationally lensed quasar. The mirage shows two images of a radio-loud quasar at redshift $z = 1.41$. The time lag between these two images is well established around one year. We detected a very prominent variation in the optical brightness of Q0957+561A at the beginning of 2009, which allowed us to predict the presence of significant intrinsic variations in multi-wavelength light curves of Q0957+561B over the first semester of 2010. To study the predicted brightness fluctuations of Q0957+561B, we conducted an X-ray, NUV, optical and NIR monitoring campaign using both ground-based and space-based facilities. The continuum NUV-optical light curves revealed evidence of a centrally irradiated, standard accretion disk. In this paper, we focus on the radial structure of the standard accretion disk and the nature of the central irradiating source in the distant radio-loud active galactic nucleus (AGN).

1. Introduction

Reverberation (or echo) mapping is a time-domain technique to resolve the accretion flow in AGNs. This relies on the analysis of time-delayed responses of different emitting regions to original fluctuations in an irradiating source [1]. While concurrent X-ray-UV-optical continuum monitoring campaigns of low-redshift AGNs are leading to puzzling results (e.g., [2]), there is only one AGN at $z \geq 1$ with a continuum reverberation map: Q0957+561 [3]. The $z = 1.41$ radio-loud quasar Q0957+561 suffers a strong gravitational lens effect, so one observes two images Q0957+561A and Q0957+561B from Earth. Intrinsic flux variations in Q0957+561B lag those in Q0957+561A by about 14 months [4], and we taken advantage of this time delay between images. Optical follow-up observations in late 2008 and the first semester of 2009 showed very prominent variations in Q0957+561A [5], which enabled us to know in advance the flaring behaviour of Q0957+561B during the first semester of 2010, and to use the Liverpool Robotic Telescope (Sloan *griz* bands), the UVOT on board the Swift satellite (U band) and the Chandra Space Telescope (X-rays) for such a time period.

From the Ugr light curves of Q0957+561B in 2010, we measured interband delays of several days that were consistent with a centrally irradiated, standard accretion disk [3]. In this scenario, a flaring source very close to the central supermassive black hole illuminates a standard accretion disk. The central flares are then thermally reprocessed into FUV-MUV variations in the inner disk to produce the observed NUV-optical variability. In Section 2 we present the NIR observations and the corresponding light curves, which were not discussed in [3]. These new NIR data are used to check the accretion scenario and discuss in detail the disk radial structure. In

Section 3 we infer possible reconstructions of the effective luminosity of the central irradiating source from the NUV-optical-NIR light curves. Our main conclusions appear in Section 4.

2. NIR observations and the accretion scenario

In 2010, we conducted a NIR monitoring programme of Q0957+561 with the RATCam CCD camera on the Liverpool Robotic Telescope at La Palma, Canary Islands. The exposure times were 120 and 240 s per night in the i and z bands, respectively. The pre-processing steps included in the telescope pipeline are: bias subtraction, overscan trimming and flatfielding. In addition, we interpolate over bad pixels using the bad pixel mask, clean some cosmic rays and remove fringe patterns. Our crowded-field photometry pipeline is then used to produce instrumental fluxes of both quasar images over 54 epochs. To achieve a reasonable compromise between photometric quality and sampling rate, later we apply thresholds on the signal-to-noise ratio in the i and z bands. The final processing stage consists of the conversion from instrumental magnitudes to physical fluxes (in mJy), and the final NIR fluxes are available at `http://grupos.unican.es/glendama/LQLMII_DR.htm`. We also display the NIR light curves of Q0957+561B in Fig. 1a. This includes 50 data points at λ_o = 7481 Å (i-band) and 45 data points at λ_o = 8931 Å (z-band). While the i-band flux accuracy is 1.4%, the z-band flux accuracy is only 2.0%. Fig. 1b includes all NUV-optical-NIR records of Q0957+561B in 2010.

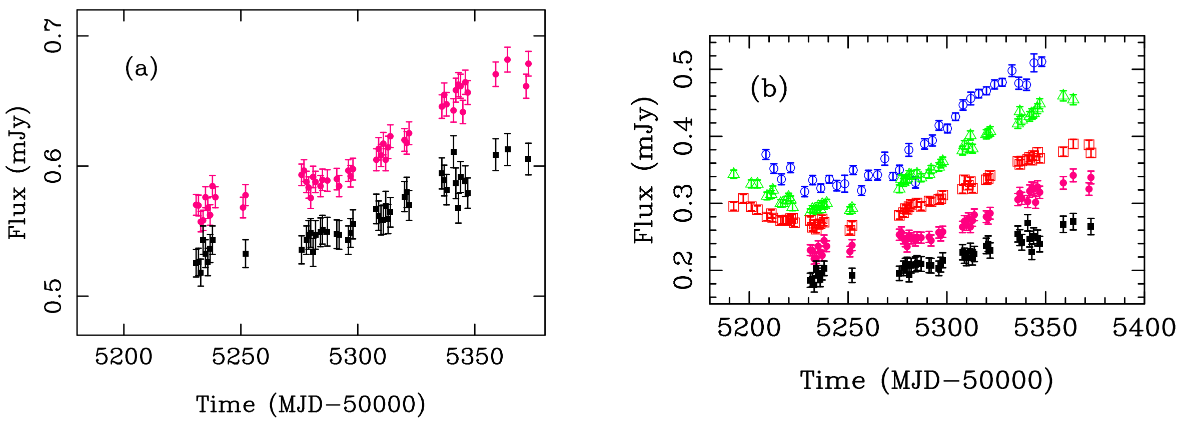

Figure 1. (a) Fluxes of Q0957+561B in the i [●] and z [■] bands of the SDSS photometric system in 2010. (b) NUV-optical-NIR light curves of Q0957+561B in 2010: U [○], g - 0.13 mJy [△], r - 0.25 mJy [□], i - 0.34 mJy [●] and z - 0.34 mJy [■] bands. This multiwavelength monitoring campaign was planned after an optical alert in 2009 (see main text).

As a result of the cosmic expansion, observed wavelengths (λ_o) are longer than emission wavelengths at the AGN (λ). Hence, our NUV-optical [3] and NIR light curves of Q0957+561B in 2010 correspond to UV continuum sources at z = 1.41 (emission at λ = 1438–3706 Å). In our recent paper [3], we have only analysed the best data from each telescope. This approach precluded the use of NIR data, since the photometric accuracy and time coverage in the iz bands are worse than those in the gr bands. Here, using a χ^2 minimization (e.g., [4]), the NIR light curves are compared to the g-band brightness record (λ = 1944 Å). We thus estimate two additional relative delays for emissions at λ = 3104 Å (i-band) and λ = 3706 Å (z-band): τ(3104 Å) - τ(1944 Å) = $9.0^{+1.3}_{-2.1}$ days and τ(3706 Å) - τ(1944 Å) = $14.0^{+3.1}_{-5.3}$ days (1σ intervals), which are used to check the inner accretion onto the supermassive black hole. These new delays confirm the scenario derived from the previous interband delays [3], i.e., all measured delays are consistent with observer-frame lags $\tau(\lambda) \propto \lambda^{4/3}$ between a central irradiating source and standard disk rings emitting at different wavelengths λ (e.g., [6]). Interestingly, the normalization based on NUV-optical data, τ(1944 Å) = 9 days, also works at λ = 3000–4000 Å (see Fig. 2).

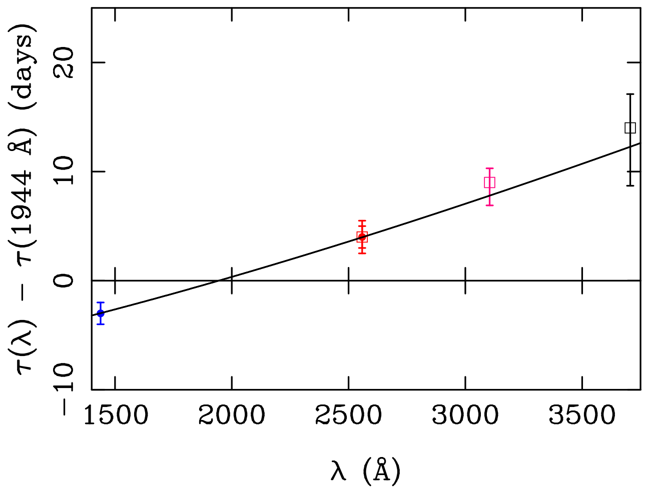

Figure 2. Relative delays using correlation functions [●] and a χ^2 minimization [□]. We show that both techniques (correlation functions and χ^2) produce similar delays at $\lambda = 2558$ Å (r-band). We also display the predictions of the centrally irradiated accretion disk with $\tau(1944\ \text{Å}) = 9$ days [——].

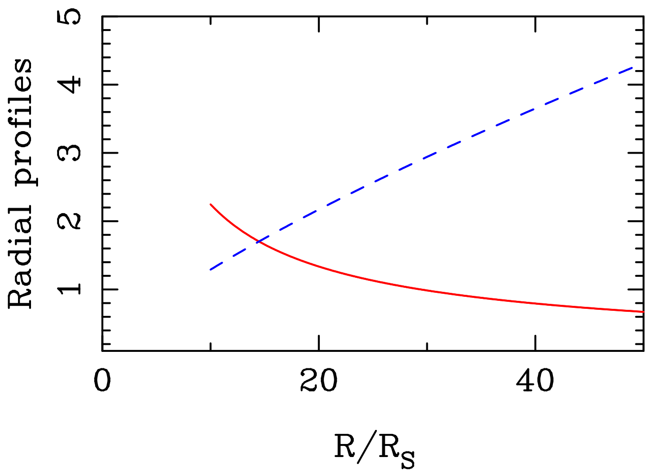

Figure 3. Radial profiles for the irradiated accretion disk in Q0957+561: temperature in 10^4 K [——] and emission peak wavelength in 10^3 Å [– – –].

The UV continuum sources ($\lambda = 1438$–3706 Å) lie within 10–30 R_S of the central black hole, where R_S is the Schwarzschild radius for a black hole mass $M = 2.5 \times 10^9 M_\odot$ [7]. If the irradiating source is just above the black hole, the disk temperature at radius $R >> R_S$ is given by (e.g., [6])

$$T(R) = [3GM\dot{M}(1 + \alpha_{\text{iv}})/8\pi\sigma R^3]^{1/4}, \tag{1}$$

where

$$\alpha_{\text{iv}} = \frac{2(1 - A)LH}{3GM\dot{M}}. \tag{2}$$

In Eqs. (1) and (2), G is the gravitation constant, σ is the Stefan constant, $\dot{M}$ is the mass accretion rate, α_{iv} is the irradiation-to-viscosity ratio, A is the disk albedo, and L and H are the luminosity and height of the central irradiating source. Each central flare propagates out at the speed of light c and arrives at radius R after an observer-frame time $\tau = (1 + z)R/c$. The temperature then rises and the peak emissivity increases, so each flare is reprocessed to roughly produce a fluctuation at $\lambda = 0.26\,[hc/kT(R)]$ (black-body emission peak), k and h being the Boltzmann constant and the Planck constant, respectively [6]. The expected $\tau - \lambda$ relationship is

$$\tau(\lambda) = 6\ (1 + z) \left[\frac{3GM\dot{M}(1 + \alpha_{\text{iv}})}{8\pi\sigma c^3}\right]^{1/3} \left(\frac{k\lambda}{hc}\right)^{4/3}, \tag{3}$$

and we compare this Eq. (3) to the observed law $\tau(\lambda) = (9 \text{ days}) \times (\lambda/1944 \text{ Å})^{4/3}$. We obtain an effective mass accretion rate $\dot{M}(1 + \alpha_{\rm iv}) = 3\ M_\odot\ \rm yr^{-1}$ that translates into two extreme accretion-irradiation regimes:

(a) $\dot{M} = 3\ M_\odot\ \rm yr^{-1}$ and $L \leq 10^{45}$ erg s^{-1}, and
(b) $\dot{M} = 1\ M_\odot\ \rm yr^{-1}$ and $L = 10^{47}$ erg s^{-1},

assuming the reasonable constraints $4(1-A)(H/3R_{\rm S}) = 1$ and $\dot{M} \geq 1\ M_\odot\ \rm yr^{-1}$ [8]. Fig. 3 shows some radial profiles for the black hole mass and effective mass accretion rate of Q0957+561.

3. Central irradiating source

If central flares are thermally reprocessed in the disk at 10–30 $R_{\rm S}$ from the central supermassive black hole, what is the source of such flares? Standard simulations of X-ray reprocessing (e.g., [9]) ruled out the possibility that the disk variability is driven by a standard corona just above the black hole. The power-law X-ray emission is plausibly originated in the base of the Q0957+561 jet at a typical height of 200 $R_{\rm S}$ [3]. Moreover, the thermal source that we detect in the Chandra X-ray spectra (kT = 0.08 keV) can not account for the observed NUV-optical-NIR variations. A central EUV (unobservable!) source seems the best candidate to illuminate the disk and drive its variability. While standard reprocessing simulations rely on the lamppost model and use observed high-energy variations to try to reproduce observed fluctuations at lower energies (presumably originated in accretion disks; e.g., [9, 3] and the last paper in [2]), low-energy ($\lambda_{\rm o}$ = 3000–10000 Å) brightness records and inverse problem techniques (e.g., [10]) can be powerful tools for reconstructing emissivities of central irradiating sources. The so-called inverse problem in reprocessing has a very promising future, and here we concentrate on direct reconstructions of the central variable (effective) luminosity of Q0957+561 based on our NUV-optical-NIR data in 2010.

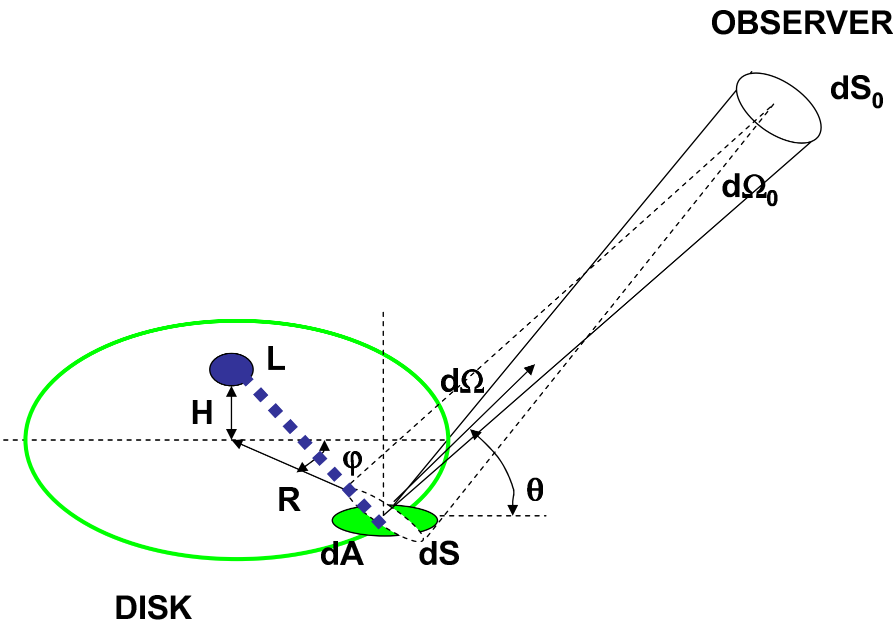

Figure 4. The standard accretion disk is illuminated by an isotropic source of luminosity L that is located at a height H above the central supermassive black hole (lamppost model). A distant observer is situated at latitude θ.

A fraction $1 - A$ of the illuminating EUV radiation would be absorbed in the disk, and then reprocessed into thermal radiation. This variable illumination would cause the variable emission of the disk. Considering the lamppost model and an observer at latitude θ (see Fig. 4), the contribution of the disk portion dA at (R, φ) to the flux received at time t_0 by the distant observer is related to the luminosity of the central source at time $t - \tau(R, \varphi; \theta)$, where $\tau(R, \varphi; \theta) = [(R^2 + H^2)^{1/2} - R\cos\theta\cos\varphi + H\sin\theta]/c$. As a result, the expected flux from the whole disk $F(\lambda_0, t_0)$ depends on different central luminosities $L(t - \tau)$ at different lags τ with respect to the emission time t. A simple approach consists of assuming an effective luminosity $L_{\rm eff}$ responsible for the disk emission by irradiation, which would correspond to an effective lag $\tau_{\rm eff}$. For each observation epoch t_0, one can minimize the difference between the modeled and observed flux: $|F_{\rm obs}(\lambda_0, t_0) - F_{\rm mod}(L_{\rm eff})|$, and thus obtain the value of $L_{\rm eff}$ for the data point at t_0. We take $M = 2.5 \times 10^9 M_\odot$ and $z = 1.41$, as well as a typical latitude $\theta = 45°$, $H = R_{\rm S}$ and $A = 1/4$. Note that the values of H and A verify the constraint $4(1 - A)(H/3R_{\rm S}) = 1$ (see above). It is not so easy to set a reasonable value of the AGN-observer transmission factor $\mu = \mu_{\rm lens} \times \mu_{\rm dust}$. This is a combination of two different contributions: the gravitational lens magnification ($\mu_{\rm lens} > 1$) and the dust extinction ($\mu_{\rm dust} < 1$) of Q0957+561B. We somewhat arbitrarily assume that both effects compensate each other, so that $\mu = 1$. First, we check the two extreme mass accretion rates that we find from the time delay analysis in Section 2, i.e., (a) $\dot{M} = 3\ M_\odot\ {\rm yr}^{-1}$ and (b) $\dot{M} = 1\ M_\odot\ {\rm yr}^{-1}$. Both extreme values lead to luminosities exceeding 10^{47} erg s^{-1}, in reasonable agreement with expected emissivities in the accretion-irradiation regime (b). Second, we select the self-consistent regime (b), and set $\dot{M} = 1\ M_\odot\ {\rm yr}^{-1}$.

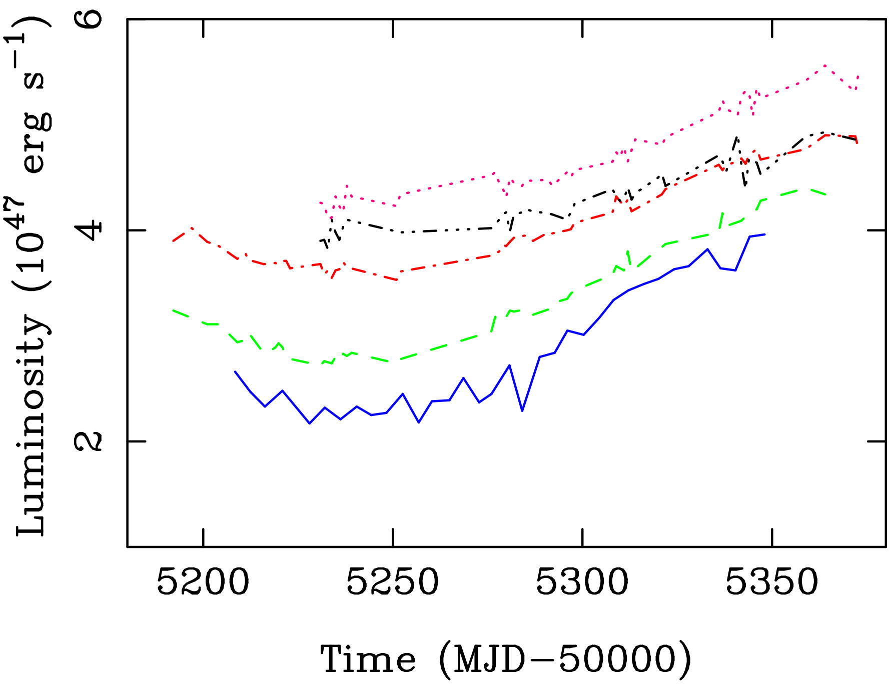

Figure 5. $L_{\rm eff} - t_0$ laws from data in the U [——], g [– – –], r [— · —], i [· · · · · ·] and z [— · · —] bands.

We infer effective luminosities of a few 10^{47} erg s^{-1} from the NUV-optical-NIR records (see Fig. 5). The effective luminosity curves are smoothed versions of the actual luminosity curve. Thus, the variability from the Swift/UVOT data (U band) is more realistic than those from the optical-NIR fluxes, since the U-band source is relatively small and the smoothing is not so important. We also remark that the luminosity offsets between the $Ugri$-based reconstructions are plausibly due to wavelength-dependent dust extinction in the host galaxy, the lensing galaxy and the Milky Way. This produces a chromatic μ, which has not been taken into account in our calculations. In addition, the ordering of our reconstructions is the expected arrangement for an unrealistic achromatic extinction.

4. Conclusions

A recent multiwavelengtht monitoring of a sharp fluctuation in the trailing image of the gravitationally lensed radio-loud quasar Q0957+561 allows us to dicuss the accretion physics in the vicinity of a distant supermassive black hole at $z = 1.41$. There is evidence for an irradiated (standard) accretion disk around the black hole, where the disk heating is mostly generated from irradiation by a central source. This central irradiating source very likely emits EUV photons and produces luminosities $\geq 10^{47}$ erg s^{-1}. Our data also support the presence of an EUV luminosity variation of about 100% on a relatively short source-frame timescale of 40 days.

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