The disk reverberation mapping of X-ray weak quasar SDSS J153913.47+395423.4

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Abstract

The widely adopted "lamppost" thermal reprocessing model, in which the variable UV/optical emission is a result of the accretion disk reprocessing of the highly fluctuating X-ray emission, can be tested by measuring inter-band time lags of quasars with different X-ray power. We report the inter-band time lag in an X-ray weak quasar, SDSS J153913.47+395423.4. **A significant cross correlation with a time delay of ~ 33 days (observed-frame)** is detected in the Zwicky Transient Facility (ZTF) g and r light curves of SDSS J153913.47+395423.4. **The observed X-ray power seems to be too weak to account for the observed inter-band cross correlation with time delay**. Hence the X-ray weak quasar, SDSS J153913.47+395423.4, is either intrinsically extremely powerful in X-ray, or the X-ray emission is not the only mechanism to drive UV/optical variability. In the former case, the required X-ray is at least 19 times stronger than observed, which requires either an exceptionally anisotropic corona or Compton thick obscuration. Alternatively, the Corona-heated Accretion disk Reprocessing (CHAR) or the EUV torus models may account for the observed time lags.

1. Introduction

The central engine of Active Galactic Nuclei (AGNs), which are powered by the accretion of gas onto supermassive black holes (SMBH), generally is too compact to be spatially resolved and can only be probed in time or spectral domains. One popular method is disk reverberation mapping, which measures the inter-band time delays of AGN disk continua. The observed time delays are from hours to days (e.g., [1, 2, 3, 4, 5]). The observed inter-band cross correlation indicates that the same physical mechanism likely drives the variations in different emission regions. One possible driving mechanism is "lamppost" thermal reprocessing (e.g., [6]). **The disk reverberation method mapping can test** the "lamppost" thermal reprocessing model. **Interestingly, the time delays are not entirely consistent with the X-ray reprocessing** of the Shakura & Sunyaev disk [7]. From the theoretical point of view, the "lamppost" thermal reprocessing model **has a long-standing energy budget problem** (e.g., [8, 9]). The ratio of the X-ray emission at 2 keV to the UV emission at 2500 Å decreases with increasing UV luminosity (see, e.g., [10, 11]). **Hence, while the X-ray illumination might be powerful enough to drive the observed UV/optical variability in low-luminosity AGNs, the same process should be inefficient in luminous quasars**.

2. SDSS J153913.47+395423.4 - spectrum and α_{OX} - L_{2500} relation

So far, the disk mapping is performed for AGNs with low luminosity (thus strong X-ray power) or X-ray normal quasars. If the "lamppost" thermal reprocessing is correct, we expect no inter-band cross correlations with time delays in the UV/optical light curves of X-ray weak quasars. **Hence, X-ray weak quasars are ideal for verifying the X-ray reprocessing and probing alternative possible UV/optical variability mechanisms**. Here we report the time delay of the g and r band continua of an X-ray weak quasar, SDSS J153913.47+395423.4.

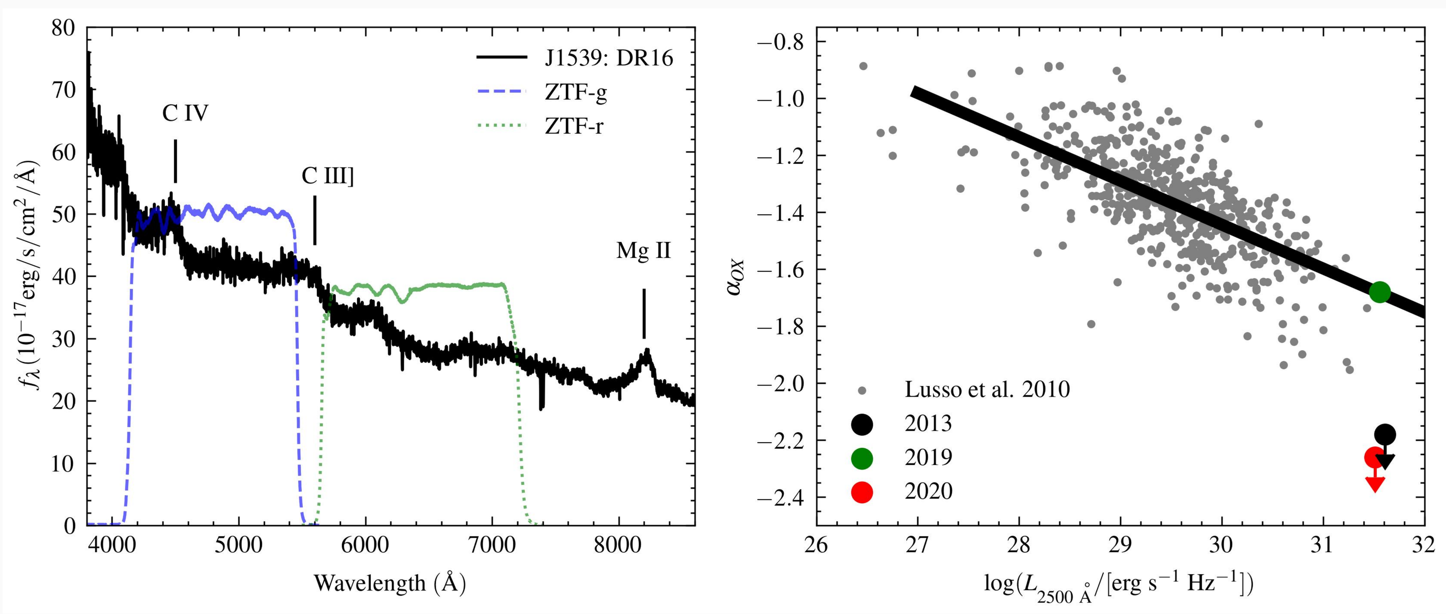

Fig. 1: Left panel: The SDSS DR16 spectrum (black curve) of SDSS J1539+3954 and the ZTF g and r filter response curves, in blue, and green, respectively. CIV and CIII] are exceptionally weak in SDSS J1539+3954. Right panel: The X-ray to UV power-law slope α_{OX} vs. the rest-frame monochromatic luminosity L_{2500}.

3. Zwicky Transient Facility g, r, and i-band light curves

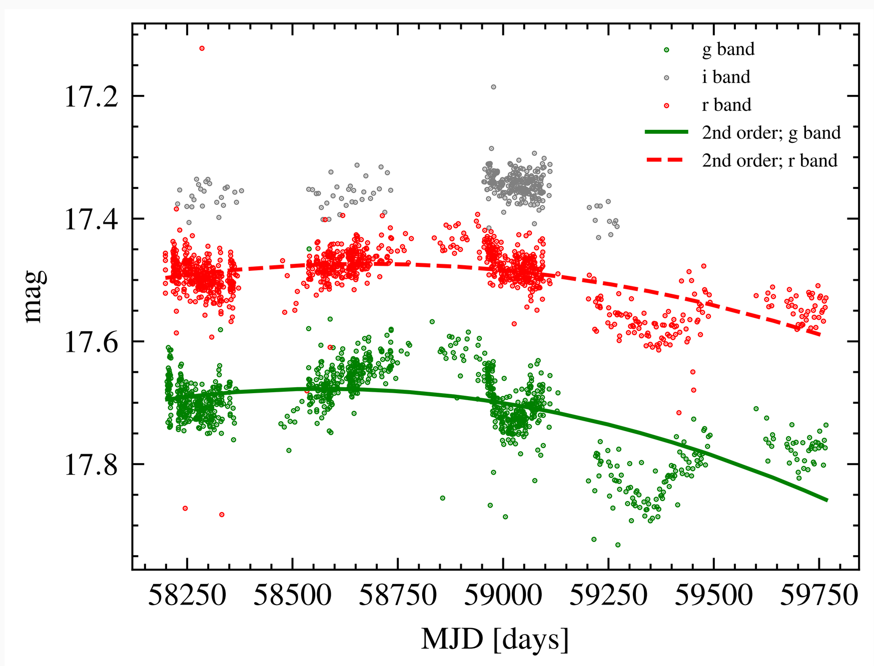

Fig. 2: The g, r, and i-band light curves of SDSS J1539+3954 from ZTF. The green solid and red dashed curves are the best-fitting second-order polynomial curves for g and r, respectively.

4. Accretion disk size

- Following Fausnaugh et al. 2018 [12] and Li et al. 2021 [13]:

$$\tau_{2500,\mathrm{th}} = 0.128 \times 5.04 \left(\frac{M_{\mathrm{BH}}}{10^8 \mathrm{M}_\odot}\right)^{2/3} \left(\frac{f_{\mathrm{Edd}}}{0.1}\right)^{1/3} \text{ days} \quad (1)$$

- The theoretical time lag in the observed frame is $\tau_{\mathrm{gr,th}}(1+z) = 11.2$ days, **which is smaller than the observed one** ($\tau_{\mathrm{gr,obs}} \sim 33$ days) **by a factor of three**,
- **This larger-than-expected time lag result is consistent** with many previous studies (e.g., [1, 14, 15, 4, 5]).

5. Correlation coefficient evaluation

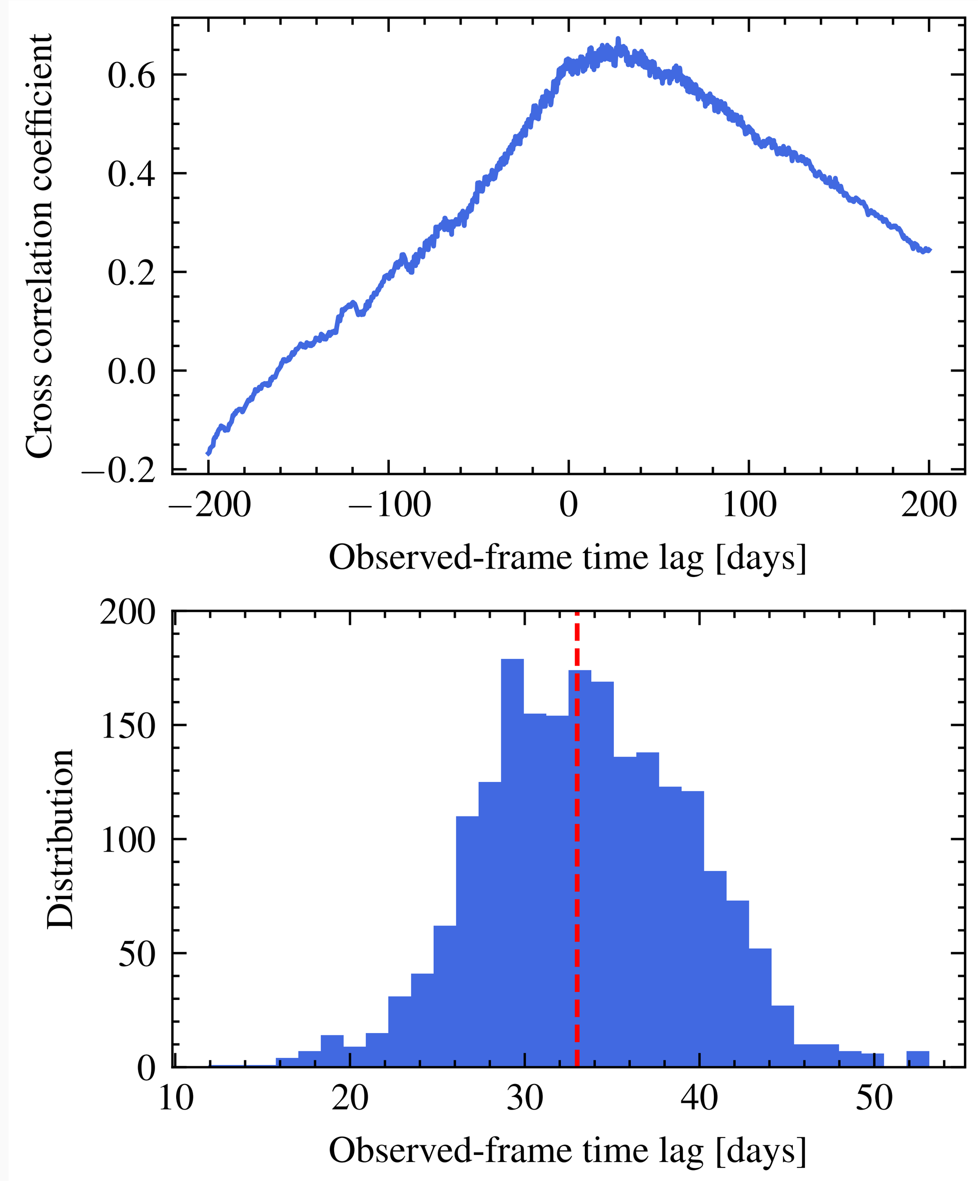

Fig. 3: The observed-frame time lag between g and r bands vs correlation coefficient and its centroid distribution. The red dashed line indicates the median value

6. The radius-luminosity relation

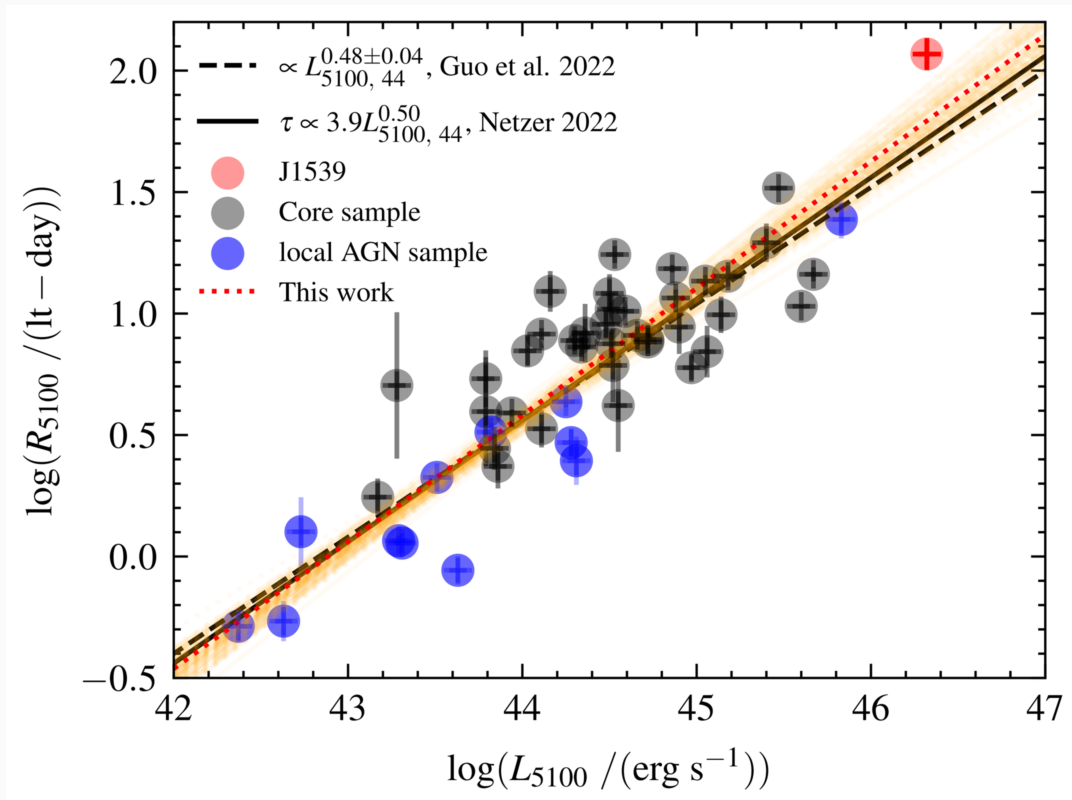

Fig. 4: The radius-luminosity relation at 5100 Å. The best linear fit (red dotted line) applies to all sources with a typical luminosity uncertainty of 0.05 dex. The black solid and dashed lines correspond to the relations in [15] and [4].

Conclusion

In this study, we use ZTF observations to explore the inter-band time lag between g and r for an X-ray weak quasar, SDSS J1539+3954. Our main findings can be summarized as follows.

- **A significant cross correlation with a time delay of $\tau_{\mathrm{gr,obs}} = 33^{+6}_{-5}$ days (observed-frame) is detected**. Our observed time delay is about three times larger than the X-ray reprocessing in a Shakura & Sunyaev disk if the virial black-hole mass is valid.
- To understand the observed time delay, the X-ray power of SDSS J1539+3954 should be at least 19 times larger than the X-ray observations. **Such inconsistency in the "lamppost" thermal reprocessing model is possible if: a. the corona emission is anisotropic; b. strong absorption is present (e.g., by winds)**.
- Due to the high luminosity of SDSS J1539+3954 we were able to extend the range of radius-luminosity relation (see Fig. 4). Given its weak-line nature (i.e., the diffuse continuum from the inner BLR clouds should also be weak), one would expect that SDSS J1539+3954 falls below the radius-luminosity relation if the diffuse continuum is the only mechanism accounted to this relation. **The inconsistency between our observation and expectation suggests that other/additional mechanisms (e.g., the CHAR model) could also contribute to the R_{5100}^{rest}-luminosity relation**, (e.g., the CHAR model, [16] or the EUV reprocessing model can explain our results [17]).

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