THE DISCOVERY OF TIMESCALE-DEPENDENT COLOR VARIABILITY OF QUASARS

Yu-Han Sun$^1$, Jun-Xian Wang$^1$, Xiao-Yang Chen$^1$, and Zhen-Ya Zheng$^2$

$^1$CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei, Anhui 230026, China; sunyh92@mail.ustc.edu.cn, jxw@ustc.edu.cn
$^2$School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA

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ABSTRACT

Quasars are variable on timescales from days to years in UV/optical and generally appear bluer while they brighten. The physics behind the variations in fluxes and colors remains unclear. Using Sloan Digital Sky Survey g- and r-band photometric monitoring data for quasars in Stripe 82, we find that although the flux variation amplitude increases with timescale, the color variability exhibits the opposite behavior. The color variability of quasars is prominent at timescales as short as $\sim 10$ days, but gradually reduces toward timescales up to years. In other words, the variable emission at shorter timescales is bluer than that at longer timescales. This timescale dependence is clearly and consistently detected at all redshifts from $z = 0$ to 3.5; thus, it cannot be due to contamination to broadband photometry from emission lines that do not respond to fast continuum variations. The discovery directly rules out the possibility that simply attributes the color variability to contamination from a non-variable redder component such as the host galaxy. It cannot be interpreted as changes in global accretion rate either. The thermal accretion disk fluctuation model is favored in the sense that fluctuations in the inner, hotter region of the disk are responsible for short-term variations, while longer-term and stronger variations are expected from the larger and cooler disk region. An interesting implication is that one can use quasar variations at different timescales to probe disk emission at different radii.

Key words: accretion, accretion disks – galaxies: active – galaxies: nuclei – quasars: general

Online-only material: color figures

1. INTRODUCTION

Active galactic nuclei (AGNs), including quasars and their low-luminosity analogs, have been found to be variable from radio to X-ray and gamma-ray. It is widely accepted that the optical and UV emission of quasars, which are variable on timescales of days to years, are dominated by thermal emission (i.e., the big blue bump) from the accretion disk surrounding the central supermassive black hole. Note that there are still challenges from observations to accretion disk models (e.g., Davis et al. 2007; Bonning et al. 2007; Lawrence 2012).

Studying the variations of UV/optical emission provides a useful approach to probe the physics of the accretion disk. Meanwhile, variations are also essential to reverberation mapping studies, including the mapping of the broad emission line region, dusty torus, and accretion disk (e.g., Peterson 1993; Suganuma et al. 2006; Collier et al. 1999). AGNs can also be efficiently selected from photometric surveys based on variations (e.g., Sesar et al. 2007).

The UV/optical variations in AGNs are generally stochastic and could be modeled with a damped random walk process (Kelly et al. 2009; Kozlowski et al. 2010; MacLeod et al. 2010; Zu et al. 2013) on timescales of weeks to years. Also note that on shorter timescales, the power density spectra of Kepler AGNs appear much steeper, with slopes of $-2.6$ to $-3.3$ (Mushotzky et al. 2011), comparing to brown noise ($S \sim f^{-2}$) from random walk processes.

The UV/optical variations in AGNs are also wavelength dependent. AGNs generally show larger variation amplitudes in bluer bands (Cristiani et al. 1997;Giveon et al. 1999; Hawkins 2003; Vanden Berk et al. 2004). The wavelength-dependent variation pattern is also seen via a different concept that AGNs normally appear bluer when they get brighter (Giveon et al. 1999; Wilhite et al. 2005; Sakata et al. 2011; Schmidt et al. 2012; Wamsteker et al. 1990; Webb & Malkan 2000), showing the variable emission is bluer than the stable or less variable ones.

The nature and origin of such a “bluer when brighter” pattern is still under debate. Contaminations from the host galaxies may produce a “bluer when brighter” pattern as the host galaxy emission is redder and stable (e.g., Hawkins 2003). Pollution to spectra or broadband photometry by less variable components such as the small blue bump (Paltani & Walter 1996) and emission lines may also produce a “bluer when brighter” pattern, but only in certain wavelength ranges, and may even produce the reverse pattern ("redder when brighter") at different wavelength ranges (e.g., Schmidt et al. 2012). Besides this, the spectra of the variable emission in AGNs appear consistent with predictions from accretion disk theory (Pereyra et al. 2006; Li & Cao 2008; Sakata et al. 2011; Zuo et al. 2012; Gu & Li 2013). This stimulates assumptions that attribute AGN variations to changes in mass accretion rates.

In this work, using Sloan Digital Sky Survey (SDSS) monitoring data of quasars in Stripe 82, we find that the color variation pattern in quasars is timescale dependent, providing a new and unique vision to the understanding of the color variations in AGNs. We present our analysis approach in Section 2 and the results in Section 3. In Section 4, we discuss the implications of this interesting discovery.

2. METHODOLOGY AND DATA

A “bluer when brighter” tendency in the UV/optical color variations in quasars has been well established by linear fitting multi-epoch measurements in magnitude–color space (e.g., Giveon et al. 1999; Vanden Berk et al. 2004; Wilhite et al. 2005). The trend has been confirmed by fitting the color variability in magnitude–magnitude (or flux–flux) space, which can remedy...
In order to explore the timescale dependence of the color variation in quasars, we develop a structure function approach. For each pair of epochs of an individual quasar, we define a parameter $\theta$ (in the magnitude–magnitude space, see Figure 1, we use the $g$ and $r$ bands for instance) to measure the amplitude of the color variation between two epochs and the time lag $\tau$ between two epochs to stand for the timescale of the color variation:

$$\theta(\tau) = \arctan \left( \frac{m_g(t + \tau) - m_g(t)}{m_r(t + \tau) - m_r(t)} \right). \quad (1)$$

Quasars usually brighten or darken simultaneously in the $g$ and $r$ bands, thus $\theta$ should fall in the range of $[0^\circ, 90^\circ]$). However, there are cases where quasars brighten in the $g$ band but darken in the $r$ band, or vice versa (most likely due to photometric uncertainties), yielding $\theta$ in the ranges of $[-45^\circ, 0^\circ]$ and $[90^\circ, 135^\circ]$. We restrict the valid range of $\theta$ to $[-45^\circ, 135^\circ]$, and $\theta$ outside of this range (e.g., $[135^\circ, 315^\circ]$) can be transformed into it by $-180^\circ$ (see Figure 1 and its caption). Averaging $\theta(\tau)$ over all epoch pairs within the given timescale ranges (which can be done for a single quasar with well-sampled two band light curves or for multiple quasars), we get

$$\bar{\theta}(\tau) = \frac{\sum N \theta_i(\tau)}{N}. \quad (2)$$

where $N$ stands for the number of pairs with $\tau$ falling in given ranges.

Note the inclination $\theta$ quantifies the color variability similarly to the slope of the variation in magnitude–magnitude space.
We collect all pairs of epochs within each light curve of the quasars and calculate the ensemble structure function as

$$SF(\tau) = \frac{1}{N(\tau)} \sum_i [m(t + \tau) - m(t)]^2. \quad (3)$$

We clearly see stronger variation in the g band than the r band, indicating the well-known pattern of larger variation in bluer band. The amplitudes of the variation in both bands drop with decreasing timescale and tend to flat at timescales <30 days. This shows that at smaller timescales, the structure function is dominated by photometric uncertainties. By averaging the structure function below five days, we obtain a mean value of 0.057 mag and 0.054 mag for the quasars and calculate the ensemble structure function as a function of timescale in the observed frame. The bin size of 0.08 in log space. In both panels, we dropped a couple of data bins (for instance, at ~200 days) due to too few data pairs available in those timescale bins. In the lower panel, the dashed line at $\theta = 45^\circ$ draws the boundary between “bluer when brighter” (45<) and “redder when brighter” (45>). The dotted lines plot the standard 1σ errors of $\theta$ assuming $\theta$ measured from each data pair distributes randomly within [45, 135]. Such errors are solely determined by the number of data pairs in each timescale bin and can be interpreted as the conservative upper limits to the uncertainties of observed $\theta$. The observed $\theta$ and its 1σ errors are plotted as the solid and dash-dotted lines (after and before applying the “3σ” criterion on the variation, respectively).

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

To minimize the pollution from photometric uncertainties, we further exclude pair epochs in which the flux variation in the $g$–$r$ space is statistically insignificant (<3σ). The 1σ uncertainty of the variation between two epochs in the magnitude–magnitude space was calculated by treating the photometric uncertainties of each epoch in the $g$–$r$ space as ellipses and adding the uncertainties within two ellipses along the variation quadratically (see Figure 1). The fraction of the excluded pair epochs with this approach decreases gradually from ~90% at timescales of 1–10 days to ~70% at timescale above 100 days. Note this criterion is adopted to exclude pair epochs with insignificant flux variations, independent to the significance of the color variation.

The new output $\theta$ is significantly smaller at intermediate timescales (thick solid line in Figure 3), confirming that photometric uncertainties could smear out the color variation at small timescales. Instead, at timescales <30 days, quasars likely have even stronger “bluer when brighter” tendency; however, due to the much weaker variation in fluxes at shorter timescales, this can only be examined with data points with much better photometry, such as with space-borne observations. We also note that the 3σ cut is biasing the selection to stronger flux variations at short timescales. Assuming the flux variations with different amplitudes behave similarly in color variability (i.e., with the same $\theta$) at given timescales, this bias would not affect the study in this work. Actually, Schmidt et al. (2012) have shown that at least at long timescales, lower-amplitude flux variations tend to produce more color variability. If the same trend holds at short timescales, we should expect intrinsically even stronger short-term color variability, further strengthening the results of this work. Hereafter we keep the approach of excluding epochs with flux variation <3σ in magnitude–magnitude space and limit our scope to timescales >30 days (in the observed frame).

### 3.2. Redshift Dependence

The rest frame wavelength ranges probed with SDSS g and r bands change substantially with redshift. Furthermore, it is well known that the emission lines (and Balmer continuum) in the spectra, which do not respond to fast central continuum variations, contribute differently to the broadband photometry at various redshifts (e.g., Wilhite et al. 2005; Schmidt et al. 2012). Figure 4 plots the color variability $\theta$ for the 8944 spectroscopically confirmed S82 QSOs in different observed timescale ranges as a function of redshift. The color variation shows a redshift-dependent pattern similar to Figure 4 of Schmidt et al. (2012), who has been nicely attributed to contribution from the emission line components in the quasar spectra that do not respond to continuum variation. For instance, the distributions of $\theta$ peak at $z \sim 0.7$ where Mg II line is in the g band, drop at $z > 0.95$ because Mg II line moves from the g to the r band, and reach the minimum point at $z \sim 1.4$ while Mg II line moves out from the r band. However, we see that the color variation is clearly stronger at shorter timescales at all given redshifts. This proves that the timescale-dependent color variation pattern we showed in Figure 3 is not an artificial effect related to redshift.

To better demonstrate the timescale dependence of the color variation at different redshifts, we divide the quasars into different redshift bins (selected by putting Hβ, Mg II, C IV or Lyα lines into the g or r band accordingly). In Figure 5, we clearly see similar timescale dependence of the color variation in different redshift bins. This further confirms that the timescale dependence reflects the variation pattern of the continuum but...
The Astrophysical Journal, 792:54 (6pp), 2014 September 1

Sun et al.

Figure 4. Amplitudes of color variation of Stripe 82 quasars (in three different timescale bins in the observed frame) as a function of redshift. While the color variation is clearly redshift dependent (also see Schmidt et al. 2012), the shorter-term variation is obviously bluer than the longer-term one at all given redshifts. (A color version of this figure is available in the online journal.)

cannot be attributed to emission lines in the spectra that only respond to variations at longer timescales.

4. DISCUSSION

We have shown with SDSS Stripe 82 monitoring data that the color variation (the “bluer when brighter” trend) in quasars is more prominent at short timescales of $\sim 10$ days and gradually reduces toward longer timescales up to several years. The “bluer when brighter” pattern may even disappear at much longer timescales if we simply extend the lines in three. This directly indicates that shorter-term variations in quasars are significantly bluer, although with smaller amplitudes in flux variation, than longer-term ones. This is because the color of the varied emission:

$$\frac{\Delta f_r}{\Delta f_g} = \frac{10^{0.4(m_r - \Delta m_r)} - 10^{0.4m_r}}{10^{0.4(m_g - \Delta m_g)} - 10^{0.4m_g}} \approx \frac{f_r}{f_g} \times \frac{\Delta m_r}{\Delta m_g} = \frac{f_r}{f_g} \times \tan(\theta(\tau)).$$

The immediate consequences of this interesting discovery and its possible physical nature are discussed below.

4.1. Can We Simply Attribute the “Bluer When Brighter” Pattern to Contamination from the Host Galaxies?

Mixing a variable component in bluer but constant color with a stable redder spectrum, such as from the host galaxy, could naturally produce a “bluer when brighter” pattern in AGNs (e.g., Hawkins 2003). Furthermore, if this is the only or dominated mechanism behind the color variation in AGNs, one can utilize a flux variation gradient method to distinguish the intrinsic spectrum of the disk (variable) emission from the (non-variable) host galaxy emission (e.g., Choloniewski 1981; Winkler et al. 1992; Winkler 1997; Pozo Nuñez et al. 2013). This possibility has been studied and discussed by many works, and contrary results have been reported (e.g., Woo et al. 2007; Walsh et al. 2009; Sakata et al. 2010, 2011). For instance, Sakata et al. (2011) found that contributions from the host galaxies are too weak to explain the observed “bluer when brighter” pattern in a small sample of 10 quasars, while Sakata et al. (2010) showed that host galaxy plus narrow emission lines are sufficient to explain the long-term “bluer when brighter” pattern in 11 nearby AGNs. Generally, the relative importance of the contamination from...
the host galaxy is wavelength and AGN-type dependent, which may help to partly explain the inconsistencies between different studies.

However, our discovery of the timescale-dependent color variations could immediately rule out the possibility of simply attributing the “bluer when brighter” pattern in AGNs to mixture of a variable disk emission with blue but constant color and a redder stable emission such as from the host galaxy, since this model predicts that the color of the variable emission is timescale independent. Furthermore, the approach to use the flux variation gradient method to separate AGN disk emission from the host galaxy contribution should be rigorously invalid.

Naturally we shall expect the color variations of Seyfert galaxies, the less luminous analog of quasars, should be similarly timescale dependent. If so, this can help to solve the discrepancies in observations that show that the host galaxy emission is insufficient to explain the observed color variations in quasars (e.g., Sakata et al. 2011) while the long-term color variations in Seyfert galaxies are rather weak or non-detectable after subtracting host galaxy contribution (e.g., Woo et al. 2007; Walsh et al. 2009; Sakata et al. 2010). We have shown that in SDSS quasars, the color variations are prominent at timescales of ~30 days but much weaker at timescales of a couple of years. For Seyfert galaxies that harbor less massive black holes compared with quasars, the corresponding timescales could be lower by a factor ~100 (black hole mass of 10^7 M_☉ versus 10^8 M_☉, for instance). Hence the color variations in Seyfert galaxies are expected to be much weaker at given observed timescales when compared with quasars.

4.2. Changes in Global Accretion Rate?

Pereyra et al. (2006) reported that the variable quasar spectrum (the composite differential spectrum between two epochs of observations for hundreds of SDSS quasars) in UV/optical could be well fitted by a standard accretion disk model with changes in accretion rate. They therefore proposed that the variations in quasars could be simply caused by changes in global accretion rates and quasars appear bluer when they brighten because of higher disk temperature in cases of larger accretion rate. This scenario is further supported by later studies (Li & Cao 2008; Sakata et al. 2011; Zao et al. 2012; Gu & Li 2013). Note that this interpretation relies on the validity of the assumption that timescale of the global accretion rate variation could be as short as days to months, which is under debate since the viscous timescale of the accretion disk is expected to be much longer in AGNs.

In this scenario, the color and flux of each quasar are simply determined by its global accretion rate, and its variation follows a fixed smooth monotonic curve in g−r magnitude–magnitude space. The local slope of the curve represents the color variability θ as shown in Figure 1, and in this scheme, short-term variations simply accumulate into long-term ones along the fixed curve in magnitude–magnitude space. If short-term color variability is strong (i.e., with small θ), the accumulated long-term color variability should have similarly small θ. In other words, the color variability behavior is expected to be timescale independent. This is directly rejected by the finding of this work, indicating the observed variation in quasars cannot be simply explained as changes in accretion rate. This conclusion is also consistent with a few recent works that either show that accretion rate changes cannot model the variation emission of quasars in Stripe 82 (Ruan et al. 2014; Kokubo et al. 2014), or the color variations in individual quasars are much more pronounced than the range of color seen in quasars with different accretion rates (Schmidt et al. 2012).

4.3. The Nature of the Variation and Color Variability

The fact that long-term optical light curves of quasars could be described as damped random walk processes with characteristic timescales comparable with thermal timescales suggests that the variations are due to thermal fluctuations in the accretion disk, likely driven by magnetic field related stochastic process (e.g., Kelly et al. 2009; MacLeod et al. 2010). Interestingly, Ruan et al. (2014) proposed that the spectral (color) variability of quasars could also be reproduced by a simple inhomogeneous disk model with large localized temperature fluctuations.

Within this frame, we discuss implications of the discovery presented in this work. As we have pointed out, the timescale dependence of color variations indicates long-term variations cannot be simply regarded as accumulation with time of stochastic short-term ones. Instead, variations at different timescales have different colors. A natural explanation is that short-term variations are dominated by thermal fluctuations in the innermost region of the accretion disk where the disk is hotter and the disk emission is bluer, while longer-term variations are produced over larger scales with lower effective disk temperature. Short-term fluctuations can also occur at larger disk radius, but could have been smeared out by large number of random events over large disk surface. Also, only longer-term variations could be detected at larger physical scales, yielding less blue variations. It is also possible that the disk fluctuations propagate from the inner to the outer region, and only fluctuations with larger amplitudes could propagate to larger radii and last longer. This may also explain that the variation in fluxes increases with timescale, and could be verified with Monte Carlo simulations. However, note that the velocity of the propagation is required to be very fast—even close to the speed of light—as required by the simultaneity of multi-color variations (e.g., Gaskell 2008). Meanwhile, an immediate consequence is that one can use variations at different timescales to probe the disk emission at different radii. The timescale dependence could also be used to constrain/refine the disk fluctuation models (e.g., Dexter & Agol 2011; Ruan et al. 2014). Further extensive studies on these issues are ongoing and will be presented in forthcoming paper(s).

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