Spectral Energy Distributions of Candidate Periodically-Variable Quasars: Testing the Binary Black Hole Hypothesis

Hengxiao Guo,1,2⋆ Xin Liu,1,2 Zafar Tayyba,3 Wei-Ting Liao1,2

1 Department of Astronomy, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
2 National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, 605 East Springfield Avenue, Champaign, IL 61820, USA
3 Australian Astronomical Observatory, PO Box 915, North Ryde, NSW 1670, Australia

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ABSTRACT

Periodic quasars are candidates for binary supermassive black holes (BSBHs) efficiently emitting low frequency gravitational waves. Recently, ~150 candidates were identified from optical synoptic surveys. However, they may be false positives caused by stochastic quasar variability given the few cycles covered (typically 1.5). To independently test the binary hypothesis, we search for evidence of truncated or gapped circumbinary accretion disks (CBDs) in their spectral energy distributions (SEDs). Our work is motivated by CBD simulations that predict flux deficits as cutoffs from central cavities opened by secondaries or notches from minidisks around both BHs. We find that candidate periodic quasars show SEDs similar to those of control quasars matched in redshift and luminosity. While seven of 138 candidates show a blue cutoff in the IR-optical-UV SED, which may represent CBDs with central cavities, the red SED fraction is similar to that in control quasars, suggesting no correlation between periodicity and SED anomaly. Alternatively, dust reddening may cause red SEDs. The fraction of extremely radio-loud quasars, i.e., blazars (with \( R > 100 \)), is tentatively higher than that in control quasars (at 2.5σ). Our results suggest that, assuming most periodic candidates are robust, IR-optical-UV SEDs of CBDs are similar to those of accretion disks of single BHs, if the periodicity is driven by BSBHs; the higher blazar fraction may signal precessing radio jets. Alternatively, most current candidate periodic quasars identified from few-cycle light curves may be false positives. Their tentatively higher blazar fraction and lower Eddington ratios may both be caused by selection biases.

Key words: accretion discs – black hole physics – galaxies: active – galaxies: nuclei – quasars: general

1 INTRODUCTION

The observed growths of structures suggest that mergers of galaxies, and by extension, their central supermassive black holes (Kormendy & Richstone 1995; Kormendy & Ho 2013) (SMBHs), should be common throughout most of cosmic history (e.g., Begelman et al. 1980; Kauffmann & Haehnelt 2000; Milosavljević & Merritt 2001; Haehnelt & Kauffmann 2002; Yu 2002; Volonteri et al. 2003; Hopkins et al. 2008; Blecha et al. 2013; Steinborn et al. 2016). Low frequency gravitational waves (GWs) are expected from the final coalescence of merging SMBHs. As a major target in the emerging new field of gravitational astronomy, binary supermassive black holes (BSBHs) provide a “standard siren” for cosmology and a direct test-bed for strong-field general relativity (e.g., Hughes 2009; Centrella et al. 2010; Colpi & Dotti 2011; Dotti et al. 2012; Tamanini et al. 2016). Unlike stellar mass binary black holes (which are advanced LIGO’s primary targets, e.g., Abbott et al. 2016) whose detection is largely limited to the local Universe, merging BSBHs would be detectable almost close to the edge of the observable Universe (e.g., Klein et al. 2016). The more massive, low-redshift population (i.e., in the relatively nearby Universe) is being hunted by pulsar timing arrays (e.g., Zhu et al. 2014; Shannon et al. 2015; Babak et al. 2016; Simon & Burke-Spolaor

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While the formation of BSBHs seems inevitable, direct evidence has been elusive. No confirmed case is known in the GW-dominated regime, where a binary is so close that the orbital decay is driven by emitting GWs. A critical issue is that the orbital decay of a BSBH may significantly slow down or even stall at \( \lesssim \) parsec scales, i.e., the so-called “final-parsec” problem (Begelman et al. 1980; Milosavljević et al. 2015; Fu et al. 2015; Müller-Sánchez et al. 2003; Ballo et al. 2004; Hudson et al. 2006; Liu et al. 2013; Pan et al. 2015, 2016; Bon et al. 2016; Charisi et al. 2016; Zheng et al. 2015b; Charisi et al. 2018). While a bottleneck when a binary runs out of stars to interact with, yet the gravitational wave emission is still too weak to merge the binary within the age of the universe. This bottleneck represents the largest uncertainty on the abundance of BSBH mergers as low-frequency GW sources. In theory, the bottleneck may be overcome in gaseous environments (e.g., Gould & Rix 2000; Cuadra et al. 2009; Charon et al. 2013; del Valle et al. 2015), in triaxial or axisymmetric galaxies (e.g., Khan et al. 2016; Kelley et al. 2017a), and/or by interacting with a third BH in hierarchical mergers (e.g., Blaes et al. 2002; Kulkarni & Loeb 2012; Bonetti et al. 2018).

Observational searches for BSBHs are important for testing different orbital evolutionary theories and their efficiency in solving the final-parsec problem. However, typical physical separations of BSBHs that are gravitationally bound to each other (\( \lesssim \) a few pc) are too small for direct imaging. Even VLBI cannot resolve BSBHs except for in the local universe (Burke-Spolaor 2011). CSO 0402+379 (discovered by VLBI as a double flat-spectrum radio source separated by 7 pc) remains the only robust case known (Rodriguez et al. 2006; Bansal et al. 2017). While great strides have been made in identifying dual active galactic nuclei – progenitors of BSBHs at \( \gtrsim \) kpc scales (e.g., Komossa et al. 2003; Ballo et al. 2004; Hudson et al. 2006; Liu et al. 2013; Comerford et al. 2015; Fu et al. 2015; Müller-Sánchez et al. 2015; Koss et al. 2016; Ellison et al. 2017; Liu et al. 2018b; Hou et al. 2019), there is no consensus case of BSBHs at millipc scales, i.e., in the GW regime (e.g., Bogdanović 2015; Komossa & Zensus 2016). Indirect searches are needed to identify BSBHs beyond the local universe.

Periodic quasar light curves have long been suggested as indirect evidence for candidate millipc BSBHs. The optical flux periodicity may be caused by accretion rate changes due to the intrinsic binary orbital tidal torque modulation (e.g., MacFadyen & Milosavljević 2008; Shi et al. 2012; Roedig et al. 2012; D’Orazio et al. 2013; Farris et al. 2014; Tang et al. 2018), and/or the apparent Doppler boost modulation from the highly relativistic motion of gas in the mini accretion disk around the secondary BH (e.g., D’Orazio et al. 2015b; Charisi et al. 2018). While \( \gtrsim \) 100 quasars with candidate periodicity have been proposed as evidence for BSBHs (e.g., Valtonen et al. 2008; Graham et al. 2015a, b; Liu et al. 2015, 2016; Bon et al. 2016; Charisi et al. 2016; Zheng et al. 2016; Li et al. 2019), even the strongest candidate periodicity has been shown to be subject to false positives due to stochastic quasar variability given the uneven sampling, limited time baseline, and/or relatively low sensitivity. For example, the blazar OJ 287 has been suggested to host a BSBH based on the evidence for a 12-year periodicity in the optical and radio light curves (e.g., Sillanpää et al. 1996; Valtaoja et al. 2000; Valtonen et al. 2016), where the double-peaked flares have been interpreted as the result of a secondary BH punching through the accretion disk of the primary (e.g., Takalo 1994; Valtonen et al. 2008) or accretion disk precession driven by the gravitational torque of a companion BH (e.g., Katz 1997). However, Goyal et al. (2018) has shown that out of the 117-year total duration of the available optical light curves, the observations before 1970 were highly irregularly sampled, whereas the better-sampled 1970–2017 light curve covers only \( \sim \) 3 of the claimed cycles and is too short to detect any significant periodicity over the colored-noise (i.e., stochastic component) of the power spectrum. Another example is the blazar PG1302–102, originally proposed as a BSBH candidate based on evidence for a 5-year periodicity (Graham et al. 2015b) and interpreted as due to relativistic Doppler boost (D’Orazio et al. 2015a), which has been suggested to be a false positive from random quasar variability (e.g., Vaughan et al. 2016; Liu et al. 2018a, but see Kovačević et al. 2019). Furthermore, even if the suggested periodicity were true, the physical mechanism driving the periodicity is still uncertain (e.g., Graham et al. 2015a; Charisi et al. 2018). In addition to BSBHs, alternative scenarios may be responsible for driving optical periodicity, including warped accretion disks (e.g., Tremaine & Davis 2014), radio jet procession (e.g., Kudryavtseva et al. 2011; Caproni et al. 2017; Sobacchi et al. 2017), quasi-periodic oscillations (QPOs) from e.g., Lens-Thirring procession (e.g., Stella & Vietri 1998; Ingram & Done 2011), and resonant accretion of magnetic field lines (i.e., “magnetic breathing” of the accretion disk; e.g., Willforth et al. 2010). Complementary tests are needed to verify any candidate periodicity and to sort out alternative scenarios for its physical origin.

In this work, we search for evidence of a truncated or gapped circular accretion disk in a sample of candidate periodic quasars compiled from the literature by studying their spectral energy distributions (SEDs). Given the typical \( \sim \) yearly cycles and the total black hole masses \((\sim 10^8–10^9 M_\odot)\) of the known candidate periodic quasars, the claimed BSBHs are generally expected at pre-decoupling (e.g., Kocsis & Sesana 2011; Tanaka et al. 2012; Sesana et al. 2012), i.e., when the gravitational wave inspiral timescale is still longer than the viscous timescale, where circular accretion disks should be common. The current work is motivated by circumbinary accretion disk models that predict abnormalities such as a cutoff or notch in the IR-optical-UV SED, depending on the mode of circumbinary accretion and the evolutionary state of the system (e.g., Milosavljević & Phinney 2005; Gültekin & Miller 2012; Kocsis et al. 2012; Tanaka & Haiman 2013; Tanaka et al. 2013; Gold et al. 2014; Roedig et al. 2012, 2014; Farris et al. 2015a, b; Krollik et al. 2019). For BSBHs with near-equal mass ratios (e.g., \( q \approx 0.1 \)), the secondary BH may open a cavity in the inner region of the circumbinary accretion disk resulting in a cutoff in the SED, or the two BHs may keep accreting gas from the circumbinary disk and maintaining their own minidisks producing “notches” in the SED. By searching for SED abnormalities, our current work serves as a complementary test of the BSBH hypothesis for candidate periodic quasars.

The paper is organized as follows. §2 briefly reviews theoretical predictions of BSBH circumbinary accretion disks,
focusing on abnormalities that may be observable in the optical/UV SEDs. §3 then describes the sample of candidate periodic quasars compiled from the literature and the SED data from available archival observations, as well control samples of ordinary quasars to put the results of candidate periodic quasars into context. §4 presents the SED properties of candidate periodic quasars in comparison to control quasars and the identification of a sample of seven candidate periodic quasars that show apparent SED abnormalities. §5 discusses the possible physical origins of SED abnormalities of the sample of seven candidate periodic quasars, highlighting in particular the internal reddening due to dust in the quasar host galaxies. Finally, we summarize our main results and conclude in §6. Throughout this paper, we assume a \( \Lambda \)CDM cosmology with \( \Omega_0 = 0.3 \) and \( \Omega_\Lambda = 0.7 \).

2 THEORETICAL PREDICTIONS OF BSBH CIRCUMBINARY ACCRETION DISK SEDS

Figure 1 illustrates theoretical SEDs of BSBH circumbinary accretion disks in the IR-optical-UV. Models of BSBH circumbinary accretion disks predict two characteristic morphologies that may indicate the presence of BSBHs through abnormalities in their IR-optical-UV SEDs (e.g., Roedig et al. 2014; Foord et al. 2017; Tang et al. 2018). One is a central cavity, where the inner region of the circumbinary disk is almost emptied by the secondary BH. For BSBHs with near-equal mass ratios (e.g., \( q \approx 0.1 \)), the emission would be truncated blueward of the wavelength that corresponds to the temperature of the innermost disk edge (e.g., Gültekin & Miller 2012; D’Orazio et al. 2013), producing a sharp exponential cutoff in the IR-optical-UV SED as illustrated in Figure 1 (the blue dashed curve). The other is minidisks, where there is substantial accretion onto one or both BHs, each with their own shock-heated thin disk (e.g., Yan et al. 2015; Ryan & MacFadyen 2017; Tang et al. 2018). The minidisks emit high energy radiation analogous to a single BH with a geometrically thin and optically thick disk (the red dashed and dotted curves in Figure 1). In this scenario, the emergence of a gap between the tidal radii of the minidisks and truncation radius of the circumbinary disk will lead to a notch in the SED of the total emission (the green solid curve in Figure 1).

The location of the flux deficit primarily depends on the temperature of the inner edge of the circumbinary disk (i.e., the “cutoff” temperature) given by

\[
T_{\text{cutoff}} \approx 2.0 \times 10^{4} \left[ \frac{\dot{m}}{0.1} \right]^{-1} M_{\odot}^{-1} \left( \frac{a}{100 R_{\odot}} \right)^{-3/2} \times K,
\]

where \( \dot{m} \equiv \dot{M}/M_{\text{Edd}} \) is the accretion rate in Eddington units, \( \eta \) is the radiative efficiency, \( M_{\odot} \equiv M_{\text{BH}}/(10^{8} M_{\odot}) \) is the total binary BH mass in units of \( 10^{8} M_{\odot} \), \( a \) is the binary’s semimajor axis, and \( R_{\odot} \equiv G M_{\odot}/c^{2} \) is the gravitational radius (Roedig et al. 2014). Figure 1 shows an example where we assume \( \dot{m} = 0.1, M_{\odot} = 1, \eta = 0.1, \) and \( a = 50 R_{\odot} \), resulting in \( T_{\text{cutoff}} \approx 11,000 \) K, which corresponds to 2600 Å based on Wien’s law. The deepest portion of the notch happens around \( T_{\text{notch}} \approx 4 T_{0} \), where \( T_{0} = 2^{1/2} T_{\text{cutoff}} \) is the characteristic temperature of the accretion disk of a single BH with \( r-a \) that lies between the hottest temperature of the circumbinary disk (truncated at \( \sim 2a \); Farris et al. 2014) and the coldest temperature in the minidisks (extended to \( \sim a/2 \); Paczynski 1977). The entire notch ranges from about \( \epsilon \equiv k T \approx 1 \) to \( 15 k T_{0} \), where \( k \) is the Boltzmann constant. The exact width and depth of the notch depend on the binary mass ratio and the relative rate of gas flowing onto the two BHs. The more gas flowing onto the smaller BH, the wider and deeper the notch will be, with its center being relatively more stable. The deepest portion of the notch is at most a factor of \( \sim 3 \) fainter than single BH case (Roedig et al. 2014).

In the simple illustration, we have assumed that the thermal radiation from an accreting BSBH is the sum of the radiation from the circumbinary disk and the radiation from the two minidisks. We have ignored the contribution of streams in the cavity, which connect the minidisks and the circumbinary disk, since their contribution to the total light is expected to be less than \( \pm 10\% \) (e.g., Tang et al. 2018). We have also ignored possible smoothing effect on the notch by gas streams (e.g., d’Ascoli et al. 2018).

Figure 1 also shows the observed IR-optical-UV quasar composite SED constructed based on a sample of \( \sim 2000 \) SDSS quasars (Vanden Berk et al. 2001). The power-law index of the observed quasar composite is \( \alpha_{v,\text{obs}} = -0.44 \) over the spectral range of \( \sim 1300-5000 \) Å, whereas the theoretical value is \( \alpha_{v,\text{th}} = 1/3 \) predicted based on a multicolor blackbody model. The difference may be caused by internal dust reddening in the quasar host galaxies (e.g., Xie et al. 2016). We have scaled the theoretical power-law index to be consistent with the observed value to mimic the effect of dust reddening.

3 SAMPLE AND DATA

3.1 A Sample of Candidate Periodically-Variable Quasars Compiled from the Literature

We combine the two largest known samples of systematically selected candidate periodic quasars as described below (§3.1.1 & §3.1.2). We do not include other individually identified candidates (e.g., Zheng et al. 2016; Li et al. 2019) to focus on a more homogeneous sample.

3.1.1 The CRTS Sample from Graham et al. (2015a)

We include 111 candidate periodic quasars selected by Graham et al. (2015a, hereafter G15) using data from the Catalina Real-time Transit Survey (CRTS\(^1\)). Established in late 2007, the CRTS is a synoptic survey that covers \( \sim 33,000 \) deg\(^2\) of the sky to discover optical transients (Drake et al. 2009; Djorgovski et al. 2011). It uses data automatically collected by the three dedicated 1 m class telescopes of the Catalina Sky Survey near-Earth object project. The CRTS has produced publicly available time series down to a \( \sim \)20 mag for \( \sim 5 \times 10^{5} \) objects with an average of \( \sim 250 \) observations over a 9-year baseline.

From a parent sample of 243,500 spectroscopically confirmed quasars, G15 identified 111 candidates that show a strong Keplerian periodic signal with at least 1.5 cycles over

\(^1\) http://crts.caltech.edu
the 9-year baseline using a joint wavelet and autocorrelation function-based approach. The blazar PG1302–102 (Graham et al. 2015b) represents the strongest periodic candidate in the G15 sample.

3.1.2 The PTF Sample from Charisi et al. (2016)

We also consider 33 candidate periodic quasars selected by Charisi et al. (2016, hereafter C16) using data from the Palomar Transient Factory (PTF; Rau et al. 2009; Law et al. 2009). The PTF was an optical synoptic survey to explore the transient and variable sky. It lasted from 2009/03 to 2012/12. The observations were made at Palomar Observatory by the 1.2 m Samuel Oschin Schmidt telescope with the CHF12K camera, providing a wide field of view of 7.26 deg\(^2\). It covered \(-3000\) deg\(^2\) of the sky with a 5σ limiting magnitude of \(-20.6\) in Mould-R and \(-21.3\) in SDSS-g bands with an average 5 day cadence.

From a parent sample of 35,383 spectroscopically confirmed quasars, C16 selected 50 candidate periodic quasars with at least 1.5 cycles within the PTF baseline by identifying unusually high peak in the Lomb-Scargle periodograms of the optical light curves, whose statistical significance was assessed by simulating time series that exhibit stochastic damped random walk (Kelly et al. 2009; Kozlowski 2016a) variability. Among the 50 candidates, 33 remain significant with the re-analysis of light curves including data from the intermediate-PTF (iPTF; Cao et al. 2016; Masci et al. 2017) and CRTS. Of the 33 periodic quasar candidates from the C16 sample, we remove six that have fewer than five bands of archival photometry, resulting in a sample of 27 quasars included in our SED study.

The final sample of candidate periodic quasars included in our SED study consists of 138 spectroscopically confirmed quasars (111 from G15 and 27 from C16) in the redshift range of \(0 < z < 3.5\). Figure 2 shows the basic quasar sample properties.

3.2 Control Sample of Ordinary Quasars

To put our results into context, we construct a control sample of 1380 ordinary quasars that are matched to have the same redshift and \(\hat{\ell}\)-band absolute magnitude \(M_{i,z=2}\) distribution to those of our candidate periodic quasar sample. The control sample was drawn from the SDSS DR14 quasar catalog (Pâris et al. 2018) and is \(10x\) the size of the candidate periodic quasar sample. We use KDTree\(^2\), which looks up the nearest neighbors of any points in the redshift - \(M_{i,z=2}\) space (Maneewongvatana & Mount 1999).

Figure 2 shows the redshift and \(M_{i,z=2}\) distributions of the candidate periodic quasar sample compared to those of the control sample. Also shown are the distributions of their virial black hole mass estimates \(M_{BH}\) from Shen et al. (2011) and Kozlowski (2017) (which will be used to estimate the expected location of the SED notch/cutoff; see discussion below in §5.1), and the radio loudness parameter, \(R_{6\text{cm}/2500\text{Å}}\) defined as the flux density ratio at the rest-frame 6 cm and that at 2500 Å for the subset of those with available radio observations (see discussion below in §4.2).

3.3 SED Data from Archival Observations

We queried the archival SED data for every source in the G15 and C16 catalogs using the Vizier tool\(^3\) within 3". This results in a combined sample of 138 periodic quasars with available photometry in more than 5 bands. We adopt measurements from large systematic surveys to focus on a more homogeneous dataset. These include the Galaxy Evolution Explorer (GALEX; Martin et al. 2005), the Sloan Digital Sky Survey (SDSS; York et al. 2000), the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the Wide-field Infrared Survey (WISE; Wright et al. 2010), the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), and the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey (Becker et al. 1995).

When multi-epoch photometries are available, we take the mean value to quantify the average SED. When photometries are unavailable in some bands caused either by non-detection or by not being covered in the surveys, we repair the gaps in the UV-optical-IR SED following Richards et al. (2006b). This affects \(<5%\) of our sample without SDSS or WISE measurements, and \(<30%\) without 2MASS or GALEX measurements. The gaps are repaired by extrapolating the flux density in the nearest neighboring band.

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\(^2\) https://docs.scipy.org/doc/scipy-0.15.1/reference/generated/scipy.spatial.KDTree.query.html

\(^3\) http://vizier.u-strasbg.fr/vizier/sed/
assuming the average SED of optically bright, non-blazar quasars (including both radio-quiet and radio-loud objects; Shang et al. 2011).

To calculate the radio loudness parameter $R_{6\text{ cm}/2500\text{ Å}}$ we adopt the 1.4 and 5 GHz data to calculate the flux density at the rest-frame 6 cm. For the 1.4 GHz detected sources without 5 GHz data, we extrapolate the SED assuming a radio spectral index $\alpha = -0.5$, where $F_{\nu} \propto \nu^\alpha$.

All SEDs have been shifted to the quasar’s rest frame and normalized to a small window (50 Å around 7625 Å) close to the SDSS $i$ band which is chosen to be relatively free of strong emission lines. Galactic extinctions have been applied using the extinction map of Schlegel et al. (1998) assuming the reddening law of Cardelli et al. (1989).

4 ANALYSIS AND RESULTS

To explore possible circumbinary accretion signatures in the SEDs of candidate periodic quasars, we first construct their mean SED and compare with that of the control quasars to look for any systematic difference between the two populations (§4.1 & §4.2). We then inspect the SEDs of individual candidate periodic quasars to look for evidence of any significant deviations from typical quasar SEDs based on a color selection and identify a sample of potential “outliers” with abnormally red SEDs (§4.3).

4.1 The Mean IR-Optical-UV SED of Candidate Periodic Quasars Is Similar to That of Control Quasars

Figure 3 shows the composite SED of the sample of 138 candidate periodic quasars. We show both the mean value (large filled symbols) and the 1-$\sigma$ dispersion (error bars) of the sample, as well as the individual objects (small ones). Also shown for comparison is the composite SED of the control sample of ordinary quasars that are matched to have the same redshift and $i$-band absolute magnitude distributions to those of the candidate periodic quasars (with the mean value shown in solid red and the 1-$\sigma$ ranges shown in dashed red), as well as the average SED of optically bright, non-blazar quasars of Shang et al. (2011).

The mean IR-Optical-UV SED of candidate periodic quasars is similar to that of both the control sample of ordinary quasars (in terms of both the mean value and the 1-$\sigma$ dispersion) and the Shang et al. (2011) sample of optically bright, non-blazar quasars. There is no evidence for any systematic difference or abnormal features, such as a notch or a cutoff. Our results do not change when we remove those objects with repaired SED gaps.

4.2 Candidate Periodically-Variable Quasars Have A Higher Blazar Fraction than That of Control Quasars

Figure 3 also shows the composite radio SED of the radio-detected subset of 22 objects out of the 138 candidate periodic quasars. The average radio SED is similar to that of the radio-detected subset of 200 objects in the control sample of ordinary quasars, and is in between the radio-quiet (RQ; black dashed) and radio-loud (RL; black dotted) sub-populations of the Shang et al. (2011) sample of optically bright, non-blazar quasars.

As shown in Figure 2, while the radio-detected fraction of the candidate periodic quasars (22 out of 138, or $\sim 16\pm3\%$ where the uncertainty represents 1$\sigma$ Poisson error) is consistent with that of control quasars (200 out of 1380, or $\sim 14\pm3\%$), the radio-loud (i.e., $R > 10$) fraction (19 out of 138, or $\sim 14\pm3\%$) is higher than control quasars (120 out of 1380, or $\sim 9\pm3\%$), although only at the $\sim 1.5\sigma$ significance level. In particular, the fraction of blazars, i.e., the extremely radio-loud population with $R > 100$ (13 out of 138, or $\sim 9\pm3\%$), is tentatively higher than that of control quasars (50 out of 1380, or $\sim 4\pm2\%$) at the $\sim 2.5\sigma$ level.

4.3 SED Properties of Individual Candidates: Identifying “Outliers” by Selecting Red Quasars

Some subtle, abnormal features may have been smoothed out due to the averaging effect in producing the composite SEDs. To investigate this possibility, we now inspect more closely the SED properties of individual candidate periodic quasars.

As discussed in §4 and illustrated in Figure 1, both the cutoff due to a central cavity and the notch produced by minidisks in circumbinary accretion disks will cause the a flux deficit in the bluer part of the IR-optical-UV quasar spectrum. Therefore, we can select possible “outliers” by
identifying abnormally red quasars. We define an empirical color criterion to select abnormally red quasars, which is given by:

\[
\begin{align*}
    \text{NUV} - r > 2, & \text{ when } z \leq 1, \\
    u - i > 1.5, & \text{ when } 1 < z \leq 2, \\
    g - z > 1.3, & \text{ when } 2 < z \lesssim 3.
\end{align*}
\]

For \( z > 1 \) quasars, the two color cuts are estimated assuming a rest-frame reddened power-law spectrum with \( f_\lambda \propto \lambda^{0.9} \) but k-corrected to higher redshifts.

Figure 3. Rest-frame composite SED for candidate periodic quasars. Big symbols with error bars represent the geometric mean and the 1σ dispersion, whereas small symbols denote individual candidate periodic quasars. For comparison, the solid and dashed red curves show the mean composite SED for control quasars and their 1σ dispersion. Also shown for context are the average SEDs of radio-quiet (RQ; black dashed) and radio-loud (RL; black dotted) optically bright, non-blazar quasars from Shang et al. (2011). All SEDs have been normalized to SDSS \textit{i} band.

Figure 4. Color selection of candidate periodic quasars with abnormally red SEDs using the criterion given by Equation 2. Panels show the three redshift ranges in which different color cuts are applied (dashed lines). Big black open circles represent candidate periodic quasars that show abnormally red colors. Small grey dots denote control quasars. The red SED fraction of candidate periodic quasars (\( \sim 5 \pm 2\% \)) is consistent with that in control quasars (\( \sim 6 \pm 1\% \)). See §4.3 for details.

Figure 4 displays the NUV−\( r \), \( u - i \) and \( g - z \) color vs.redshift for all the candidate periodic quasars in our SED sample. It illustrates the color selection for objects at different redshift regimes. Seven red quasars satisfy Equation 2 (shown as black open circles in Figure 4, including four objects from G15 and three objects from C16), all of which are at \( z < 1 \). We discuss two individual quasars in detail in Appendix A.

Figure 5 shows the individual SEDs and SDSS spectra for the seven red quasars. Also shown for comparison are
SEDs for control samples of ordinary quasars that are in-
 dividually drawn to match the redshift and $i$-band absolute
 magnitude for each particular quasar. Compared to the
 control sample, all the red quasars show significant flux defi-
 cits in the bluer part of the SED by selection. While being a rela-
 tively rare population, the fraction of red quasars among
 the parent sample of candidate periodic quasars (7 out of
 $138$, or $\sim5\pm2\%$) is consistent with that in the control sample
 of ordinary quasars (89 out of 1380, or $\sim6\pm1\%$).

5 DISCUSSION

5.1 Comparison with Circumbinary Accretion
Disk Models for Candidate Periodic Quasars
with Red SEDs

As described in §2, we can estimate the wavelengths of
the SED cutoff or notch using the characteristic tempera-
tures $T_{\text{cutoff}}$ and $T_{\text{notch}}$ using Equation 1. We adopt
the virial BH mass estimate $M_{\text{BH}}$ of Shen et al. (2011) and
Kozłowski (2017) based on the width of the broad H$\beta$
emission line. The accretion rate is $\dot{m} = L_{\text{bol}}/L_{\text{Edd}}$, where
$L_{\text{Edd}} = 1.26 \times 10^{38} M_{\text{BH}}/M_{\odot}$ erg s$^{-1}$. We estimate $L_{\text{bol}}$ from
the monochromatic luminosity at 5100 Å assuming the bol-
ometric correction of Richards et al. (2006b). We assume that
the radiative efficiency of the accretion disk is $\eta = 0.1$. We esti-
mate the binary’s semimajor axis using the candidate
periods reported by G15 and C16 assuming a circular orbit
and that the binary orbital period is the same as the period in
the optical light curve. Table 1 lists the resulting charac-
teristic temperatures and the corresponding wavelengths
of the expected SED cutoff and notch and the depth of the
deepest notch.

As shown in Figure 5, the expected SED cutoff wave-
length is close to the location where the SEDs of BSBH can-
didates start to be systematically redder than those of the
control quasars, which verifies our color selection. So by fur-
ther applying the appropriate color selection criterion ($\pm 4.3$),
all the seven candidate periodic quasars show SEDs that are
broadly consistent with the theoretical predictions under the
cutoff scenario. On the other hand, the notch scenario is less
likely for these candidates with red SEDs, because: (1) the
SEDs do not seem to be turning up bluward of the notch
locations, although the available SED data cannot rule out
this possibility, and (2) assuming that the notch locations
are bluer than the available SED data, the implied highest
flux deficit in the deepest portion of the SED notch is typi-
cally beyond 1.0 dex (Table 1), which is a factor of 2 of the
theoretical prediction (at most a factor of $\sim3$, i.e., 0.5 dex,
Roedig et al. 2014).

In summary, the SEDs of the color-selected periodic
candidates are broadly consistent with theoretical predic-
tions from the circumbinary accretion disk models with cut-
offs due to a central cavity, where the inner region of the
circumbinary disk is almost emptied by the secondary BH.
On the other hand, the minidisk scenario (i.e., substantial
accretion onto one or both BHs with their own minidisks)
is likely disfavored, although the available SED data can-
not rule out this possibility entirely given the limited cov-
earge and possible uncertainties in the model parameters.
One possible caveat is that there may be candidate periodic
quasars that would satisfy the minidisk scenario (i.e., with
a notch in the SED) if we relax the color criterion defined
in Equation 2. We have found no convincing candidate for
such a shallower but wide enough notch feature, however,
by examining the individual SEDs for all candidate periodic
quasars.

5.2 Alternative Explanation for the SED Outliers
in Candidate Periodic Quasars: Dust
Reddening

Alternatively, the unusually red quasar colors in the SED
outliers may be due to reddening by dust either in the im-
mediate surroundings of the accretion disks and/or in the
quasar host galaxies (e.g., Leighly et al. 2016). To explain
the observed outlier SEDs with dust reddening, we assume a
model using a composite quasar SED reddened by an extinc-
tion curve model. For the composite quasar SED, we adopt
the optical/UV composite of $\sim2000$ SDSS quasars from Van-
den Berk et al. (2001) for $\lambda < 7000$ Å and the NIR com-
posite of 27 quasars from Glikman et al. (2006) for $\lambda \geq 7000$ Å.
To model the extinction curve, we follow the Fitzpatrick &
Massa (1986, which we refer to as “FM” below) formalism
(see also Zafar et al. 2011, 2015), which is given by

\[ A_V = A_V \left( \frac{1}{R_V} k(\lambda - V) + 1 \right), \]

where

\[ k(\lambda - V) = \begin{cases} 
1 + \frac{c_1 + c_2 x + c_3 D}{c_1 + c_2 x + c_3 D + c_4 (x - c_5)^2}, & \text{when } x \leq c_5 \\
1 + \frac{c_1 + c_2 x}{c_1 + c_2 x + c_3 D} & \text{when } x > c_5
\end{cases} \]

in which $x = \lambda^{-1}$, $A_V$ is the V-band dust extinction, and
$R_V$ is the total-to-selective extinction given by $R_V = A_V / E(B-V)$.
We adopt a classical Small Magellanic Cloud type ex-
tinction curve which is commonly used to model reddened
quasar spectra (e.g., Richards et al. 2003; Hopkins et al.
2004; Glikman et al. 2012; Zafar et al., 2015), i.e., setting
$R_V = 2.93$ (Pei 1992). The FM formalism consists of two
components: (1), a UV linear component modeled by the pa-
rameters $c_1$ (intercept) and $c_2$ (slope) and the far-UV curva-
ture modeled by the parameters $c_3$ and $c_4$, and (2), a Drude
function $D$ that describes the 2175 Å bump; for simplicity,
we assume no 2175 Å bump in our model, i.e., setting $c_3 = 0$
in Equation 3. As the archival SED data does not provide
enough far-UV coverage to fit for $c_4$ and $c_5$, we fix them to
be the average values of known reddened quasars, i.e.,
assuming $c_4 = 0.62$ and $c_5 = 5.9$ (Zafar et al. 2015). Our final
extinction curve model contains three free parameters, i.e.,
$A_V$, $c_1$, and $c_2$.

We fit the dust extinction model in Equation 3 to the
GALEX-SDSS-2MASS part of the SED data with the mpfit
package (Markwardt 2009) using a least-$\chi^2$ minimization
algorithm. We have normalized the data to the $K_s$ band which
is the least affected by dust. We have scaled the SDSS spec-
tra based on the $i$ band since it is free from strong emission
lines for all objects considered. For data points without er-
ror measurements (e.g., FUV and NUV derived from force
photometry), we assume a fiducial error of 15% of the local
flux density. We assume the fitting ranges of the three pa-
rameters to be $A_V \in [0, 2]$ mag, $c_1 \in [-10.0, 2.0]$, and $c_2 \in
[0.15, 1.45]$, respectively.
Figure 5. SEDs (left column) and SDSS spectra (right column) for seven candidate periodic quasars with red colors selected by the color criterion defined in Equation 2. In the left column, solid symbols show SEDs for candidate quasars whereas lighter symbols represent control quasars for each object matched in redshift and luminosity. Solid and dotted red curves show the mean SED of control quasars and their 1σ dispersion. Blue and red dashed lines mark the expected locations of SED cutoff and notch (§2). In the right column, grey solid curves show the SDSS spectra for candidate periodic quasars. Red dashed curves represent the best-fit model constructed using a composite quasar SED (Vanden Berk et al. 2001; Glikman et al. 2006) reddened by an extinction curve model given in Equation 3 following the FM formalism (Fitzpatrick & Massa 1986; Zafar et al. 2011, 2015). The best-fit V-band dust extinction $A_v$ ranges from ~0.1 to 1.1 mag. See §5.2 for details.
The right panel of Figure 5 shows the best-fit dust extinction model for each outlier SED candidate. In general, the model agrees with the data well considering measurement uncertainties and systematic errors due to quasar variability. Table 2 lists the best-fit value and 1σ uncertainties and systematic errors due to quasar variability for each outlier SED candidate. In general, a three-free parameter dust extinction model given by Equation 3 is sufficient. Figure 6 shows the WISE W2 (i.e., [3.4]−[4.6] in mag) color-color diagram for the sample of candidate periodic quasars with red SEDs. For context, the dashed box shows the region occupied by WISE colors for candidate periodic quasars of which those with red SEDs selected by Equation 2 are circled in red. Labeled are their IDs as listed in Table 1. Shown for comparison are control quasars (black solid), and SDSS DR14 quasars (grey dotted). See §5.3 for details.

Table 1. Properties of candidate periodic quasars with red colors.

| ID        | SDSS Designation | Redshift | LogMBH (M⊙) | TSED (erg s⁻¹) | a (10⁻³ pc (R⊙)) | Period (days) | Tcutoff (K) | λcutoff (Å) | T0 (K) | λorbit range (Å) | λkick range (Å) | Depth (dec) |
|-----------|------------------|----------|-------------|----------------|------------------|---------------|-------------|-------------|-------|------------------|-----------------|------------|
| 1         | J072908.71+400836.6 | 0.074    | 7.74±0.32   | 44.92          | 1.0 (374)        | 1612 (2σ)     | 2500        | 11200       | 4300  | 400 - 6700        | 1700           | 1.6        |
| 2         | J090846.65+184037.0 | 0.745    | 7.99±0.27   | 45.10          | 3.0 (630)        | 892 (2σ)      | 1700        | 17400       | 2800  | 700 - 10400       | 2600           | 1.8        |
| 3         | J081617.73+263609.6 | 0.769    | 9.77±0.33   | 46.15          | 13 (46)          | 1162 (2σ)     | 7300        | 3900        | 12400 | 200 - 2300        | 600            | 1.5        |
| 4         | J14553.57+334360.0  | 0.885    | 8.73±0.31   | 45.51          | 5.6 (214)        | 797 (2σ)      | 3000        | 9600        | 5100  | 400 - 5700        | 1400           | 2.0        |
| 5         | J151636.22+044127.0 | 0.389    | 8.82±0.28   | 46.14          | 7.0 (218)        | 1111 (2σ)     | 4000        | 7100        | 6800  | 300 - 4300        | 1100           | 1.1        |
| 6         | J214036.77+005210.1 | 0.922    | 8.50±0.31   | 45.73          | 2.5 (162)        | 316 (1σ)      | 4800        | 6000        | 8100  | 200 - 3600        | 900            | 2.0        |
| 7         | J222135.73+173916.5 | 0.842    | 8.68±0.31   | 45.46          | 3.4 (146)        | 337 (1σ)      | 4000        | 7200        | 6800  | 300 - 4300        | 1100           | 1.2        |

Column 1: Object ID as labeled on Figure 6.
Column 2: SDSS names with J2000 coordinates given in the form of “hhmmss.ss+ddmmss.s”.
Column 3: Systemic redshift from G15 and C16.
Column 4 & 5: Virial black hole mass and bolometric luminosity from Shen et al. (2011) and Kozhurina (2017).
Column 6: Expected notched temperature and the corresponding wavelength and wavelength of the deepest notch (§2).
Column 7: Expected cutoff temperature and the corresponding wavelength at the inner edge of the circumbinary disk (§2).
Column 8 & 9: Expected notch wavelength and the corresponding range wavelength and range of the deepest notch (§2).
Column 10: Highest flux deficit observed, defined as the largest difference between the observed SED and the mean SED of control quasars.

Table 2. Best-fit dust extinction model parameters for candidate periodic quasars with red colors.

| ID        | Aν (mag) | c1  | c2  | χ² |
|-----------|----------|-----|-----|----|
| 1         | 1.08±0.13| -4.61±0.47 | 3.61±0.10 | 1.22 |
| 2         | 0.16±0.07| -4.58±0.50 | 1.02±0.47 | 1.12 |
| 3         | 0.11±0.03| -5.91±0.37 | 2.37±0.27 | 1.08 |
| 4         | 0.40±0.05| -4.72±0.39 | 2.42±0.46 | 1.21 |
| 5         | 0.16±0.11| -5.62±0.21 | 3.46±0.40 | 0.99 |
| 6         | 0.27±0.04| -6.00±0.27 | 2.35±0.22 | 0.93 |
| 7         | 0.35±0.12| -10.0±0.82 | 4.02±0.33 | 1.37 |

Column 1: Object ID as listed in Table 1.
Columns 2–4: Best-fit value and 1σ error of the free parameters in the extinction curve model given by Equation 3.
Column 5: χ² per degree of freedom in the FM model fit.

5.3 Further Evidence for Dust Reddening in Candidate Periodic Quasars with Red SEDs

We discuss further evidence for dust reddening in the candidate periodic quasars with abnormally red SEDs. Figure 6 shows the WISE W2–W3 (i.e., [4.6]–[12] in mag) vs. W1–W2 (i.e., [3.4]–[4.6] in mag) color-color diagram for the sample of candidate periodic quasars with red SEDs. For context, the dashed box shows the region occupied by WISE AGNs empirically defined by Jarrett et al. (2011), which include QSOs, Seyferts, and obscured AGNs. Also shown for comparison are the parent sample of 138 candidate periodic quasars, the control sample of ordinary quasars, as well as the SDSS DR14 quasars. The parent sample of 138 candidate periodic quasars has similar WISE colors to those of the control quasars. On the other hand, the subset candi-
date periodic quasars with abnormally red SEDs seems to be systematically skewed towards the obscured AGN population compared to control quasars and the SDSS DR14 quasars, consistent with the expectation from dust reddening. Alternatively, a central cavity in the circumbinary accretion disk opened by a secondary BH could also explain the WISE colors, considering that the mid-IR emission is primarily due to dust heated directly by the accretion disk emission.

5.4 False Positives in Current Candidate Periodic Quasars from Few-Cycle Light Curves

We discuss possible false positives in the current sample of candidate periodic quasars and their implications in the context of our SED results. Vaughan et al. (2016) has demonstrated that the candidate periodicity in the blazar PG1302−102 may be a false positive from random quasar variability (see also Liu et al. 2018a). Considering that PG1302−102 was originally proposed as the best candidate in the G15 sample, it is possible that the candidate periodic quasars in the G15 and C16 samples are subject to similar uncertainties given the limitations of the observations (e.g., limited time baselines that cover only \(\sim 1.5\) of the claimed cycles, uneven sampling and seasonal gaps in the cadence, and relatively low sensitivities).

In particular, to test the robustness of the seven candidate periodic quasars with red SEDs, we re-assess the significance of their periodicity based on the public CRTS or PTF light curves. We calculate the generalized Lomb-Scargle periodogram (Zechmeister & Kürster 2009) and construct a set of 50,000 simulated light curves for each quasar to more carefully assess the significance of any periodogram peak. We simulate the simulated light curves assuming a damped random walk model (DRW; Kelly et al. 2009; Kozlowski et al. 2010; MacLeod et al. 2010; Butler & Bloom 2011; Ruan et al. 2012; Zu et al. 2013) for the stochastic red noise variability. We tailor the simulated light curves to each quasar by sampling the probability density function of the DRW model parameters as measured from the observed light curve. Following Vaughan et al. (2016), we have also tested alternative models using the more general broken-power laws to model the power density of the observed quasar variability to verify that our results are robust against the DRW assumption, considering evidence for possible deviations from the DRW model on both short (inter-day) and long (>20 yr) timescales (e.g., Mushotzky et al. 2011; Kasliwal et al. 2015; Guo et al. 2017; Smith et al. 2018).

Table 1 lists the significance levels obtained from our re-analysis of the light curve periodicity for the seven candidates. While we were able to reproduce the reported periods, none of them exceeds the 3\(\sigma\) significance level estimated assuming the DRW model; using alternative models to the DRW assumption would lower the statistical significance even further. In two of the seven objects, the candidate periodicity is only significant at the \(\sim 1\sigma\) level.

In summary, our results are consistent with Vaughan et al. (2016) and suggest that the majority of the candidate periodic quasars reported based on few-cycle, noisy observations with uneven sampling and seasonal gaps may be false positives due to the stochastic, red noise quasar variability. In this scenario, it is unsurprising that the SEDs of candidate periodic quasars are similar to those of control quasars, considering that they would contain the same fraction of BS-BHs, if any.

5.5 Sampling Biases Driven by Variability Selection

Figure 7 shows the ensemble structure function (“SF” for short; e.g., Sun et al. 2014; Kozlowski 2016b; Sun et al. 2018) for the candidate periodic quasars (in V band for the G15 sample and in PTF R band for the C16 sample). The SF describes aperiodic luminosity fluctuations by means of the rms variability as a function of the time difference between epochs. Also shown for comparison are the ensemble SFs (in SDSS r band, which is similar to PTF R band) for a
control sample drawn from SDSS Stripe 82 quasars to match the redshift and absolute $r$-band luminosity distribution of candidate periodic quasars. Candidate periodic quasars are systematically more variable than the control sample over all the timescales considered (from days to a decade). The difference cannot be explained by the color dependence of quasar variability given the small band differences (effective central wavelength of 547.7 nm for CRTS Johnson $V$ and 623.1 nm for SDSS $r$).

The higher level of variability in candidate periodic quasars is largely driven by a selection bias considering that: (1), a significant periodicity is easier to detect in more variable quasars given the same measurement uncertainties, and (2), more variable quasars are likely to cause more false positives in periodicity searches based on few-cycle observations. More variable quasars are known to have systematically lower Eddington ratios (e.g., Rumbaugh et al. 2018; see also Guo & Gu 2014). Figure 7 shows that candidate periodic quasars have systematically lower Eddington ratios (by ~1 dex on average) than control quasars, verifying the known anti-correlation between Eddington ratio and optical quasar variability. Among the candidate periodic quasar sample, the C16 subset is on average more variable than the G15 subset (upper panel in Figure 7), because quasars from C16 have systematically lower luminosities (Figure 2) and smaller Eddington ratios (lower panel in Figure 7) than those from G15, where the color-dependent variability amplitude difference is negligible (between CRTS $V$ and PTF $R$ bands).

The tentatively higher blazar fraction found in candidate periodic quasars (§4.2) may also be naturally explained as being driven by a variability-selection bias, given that blazars are also more variable in the optical (e.g., Ruan et al. 2012). On the other hand, if most candidate periodic quasars are robust, the higher blazar fraction could imply significant optical contamination from precessing radio jets (e.g., Kudryavtseva et al. 2011; Ackermann et al. 2015; Caproni et al. 2017).

6 SUMMARY AND FUTURE WORK

Periodically-variable quasars have long been suggested as possible BSBH candidates, but alternative scenarios remain possible. As an independent and complementary test of the binary hypothesis, we have searched for evidence of a truncated or gapped circumbinary accretion disk by studying the SEDs of a sample of candidate periodic quasars. The sample combined the two largest candidate periodic quasar samples known from the CTRS and PTF surveys. Our work is motivated by recent circumbinary accretion disk simulations that predict abnormalities such as a cutoff or notch in the IR-optical-UV SED, depending on the model of circumbinary accretion and the evolutionary state of the system. To put our results into context, we have compared the SEDs of candidate periodic quasars against a control sample of ordinary quasars matched in redshift and luminosity. The work serves as a complementary test of the binary hypothesis for candidate periodic quasars. We summarize our main findings as follows.

(i) The mean SED of candidate periodic quasars is similar to that of control quasars matched in redshift and luminosity (§4.1). Our results suggest that, if the candidate periodicity is robust, the SEDs of most circumbinary accretion disks may not be significantly different from accretion disks around single BHs, at least in the IR-optical-UR part, assuming the periodicity is indeed due to a binary. Alternatively, if most of the candidate periodic quasars are false positives (§5.4), the similarity in the mean SED between candidate periodic quasars and control quasars will be unsurprising, considering that they would contain the same fraction of BSBHs.

(ii) The fraction of radio loud quasars (i.e., with radio loudness $R > 10$), and blazars (i.e., with $R > 100$) in particular, is tentatively higher than that in the control sample (§4.2). The higher radio-loud fraction, and a higher blazar fraction in particular, may be naturally explained as being driven by a variability-selection-induced sampling bias (§5.5). On the other hand, if most periodic quasar candidates are robust, the higher blazar fraction could imply contamination from a processing radio jet.

(iii) Seven of 138 candidate periodic quasars show a significant cutoff in the IR-optical-UV SED (i.e., with abnormally red colors, §4.3). However, the fraction of these SED “outliers” is similar to that in control quasars. This suggests no correlation between the occurrences of candidate optical periodicity and SED anomaly.

(iv) To explain the abnormally red colors for the seven quasars selected as SED outliers, we have compared the observations with predictions from circumbinary accretion disk models (§5.1). We find that SEDs of the color-selected periodic candidates are broadly consistent with theoretical predictions from circumbinary accretion disk models with cutoffs due to a central cavity, where the inner region of the disk is almost emptied by the secondary BH. On the other hand, the minidisk scenario, with substantial accretion onto one or both BHs with their own minidisks, is disfavored, although the limited SED data cannot rule out this possibility entirely given model uncertainties.

(v) We have also considered an alternative scenario of reddening by dust (§5.2). Following the FM formalism (Fitzpatrick & Massa 1996; see also Zafar et al. 2011, 2015), we have modeled the observed SEDs assuming an SMC type extinction curve. The best-fit dust reddening models fit the observations well, with estimated $A_V$ values ranging from ~0.1 to 1.1 mag, which are reasonable for optical quasars.

(vi) We have considered further evidence for dust reddening based on their WISE colors using the [4.6]–[12] vs. [3.4]–[4.6] color-color diagram (§5.3). Candidate periodic quasars show similar WISE colors to those of control quasars, whereas the subset with abnormally red SEDs is systematically skewed towards the obscured AGN population compared to control quasars, consistent with expectation from dust reddening. Alternatively, a central cavity in the circumbinary accretion disk opened by a secondary BH could also explain the WISE colors.

(vii) We have discussed possible false positives in the current sample of candidate periodic quasars identified from few-cycle observations (§5.4). In particular, we have reassessed the robustness of the seven candidate periodic quasars with red SEDs by calculating the generalized Lomb-Scargle periodogram based on the public CRTS or PTF light curves. We have carefully examined the significance of any periodogram peak. We have run a large set of simulated light curves that are tailored to the observed variability...
properties of each quasar. While finding consistent values with the reported periods, none of them exceeds 3σ significance, suggesting that most current candidate periodic quasars from few-cycle light curves may be false positives (see also Vaughan et al. 2016).

(viii) Finally, we have discussed sampling bias driven by optical quasar variability selection (§5.3). Based on the ensemble structure functions (Figure 7), we find that candidate periodic quasars are systematically more variable than control quasars over all timescales. The higher level of variability is largely driven by a selection bias in candidate periodic quasars. Candidate periodic quasars show systematically lower Eddington ratios than control quasars (Figure 7), verifying the known anti-correlation between Eddington ratio and optical quasar variability.

Future work should look for other SED signatures predicted by circumbinary accretion disk models such as hard X-ray excess from stream-disk collisions (e.g., Roedig et al. 2014; Farris et al. 2015b,a; Foord et al. 2017; Krollik et al. 2019). While the sample of candidate periodic quasars does not have enough archival X-ray data to test this, one should look for them in the much larger sample of ordinary quasars with archival X-ray observations (e.g., Civano et al. 2012; Coffey et al. 2019). Future work should also search for possible SED outliers to select BSBH candidates independent from the optical periodicity selection, which is still largely subject to false positives given limitations in the current light curve data. Finally, our work motivates the identification of more robust samples of candidate periodic quasars both by significantly extending the baseline coverage of existing samples with continued monitoring and by more carefully assessing the statistical significance of any candidate periodicity.

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APPENDIX A: REMARKS ON INDIVIDUAL CANDIDATE PERIODIC QUASARS WITH RED SEDS

SDSS J072908.71+400836.6 is a type 1.9 quasar. It has a broad-line component in Hα but not in Hβ (Figure A1, upper panel). Its SED and spectrum can be well fit (Figure 5) by a composite quasar SED reddened by an extinction curve model (Equation 3) with $A_V \sim 1.1$ mag (Table 2). Similarly, Mrk 231 also shows a strong broad Hα but a weak broad Hβ and a red continuum. Yan et al. (2015) has proposed Mrk 231 as a candidate BSBH whose red SED is driven by a notch in circumbinary accretion disk, while Leighly et al. (2016) suggests that it is a reddened AGN.

SDSS J153636.22+044127.0 is a quasar with double-peaked broad emission lines (with velocity a separation of 3,500 km s$^{-1}$; Figure A1, lower panel). Based on its double-peaked broad emission lines, it was identified by Boroson & Lauer (2009) as a candidate sub-pc BSBH system having masses of $10^{7.3}$ and $10^{8.9}$ M$_\odot$ separated by ~0.1 pc with an orbital period of ~100 years. Chornock et al. (2010) has suggested that it is instead an unusual double-peaked disk emitter, whose broad-line velocity splitting is driven by rotation and relativistic effects of accretion disks around single black holes (e.g., Eracleous & Halpern 2003; Lewis et al. 2010). Shen & Loeb (2010) has suggested that for large broad-line velocity splittings, the two BHs in a BSBH will be too close for their broad-line regions to be distinct, resulting in complex line profiles rather than a clear splitting of the peaks, which does not correspond to binary orbital motion. G15 has also identified SDSS J153636.22+044127.0 as a candidate BSBH but based on its candidate optical light curve periodicity with a period of ~3 years (in the observed frame), resulting in a ~10 times smaller estimate for the binary separation (~0.01 pc). Our independent analysis of the periodicity significance level is only ~2σ (§5.4 and Table 1). The CRTS light curve covers only ~3.5 cycles of the candidate periodicity, which may be too short to reject false positives from stochastic, red noise quasar variability (Vaughan et al. 2016).

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Figure A1. SDSS spectra of two interesting cases in candidate periodic quasars with red SEDs. Upper panel shows a type 1.9 quasar with a strong broad-line component in Hα but not in Hβ. Lower panel shows a quasar with a double-peaked broad emission line, which has been proposed as a candidate sub-pc SBHB by Boroson & Lauer (2009) and suggested as an unusual accretion disk emitter by Chornock et al. (2010).