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Supermassive Black Hole Binary Candidates from the Pan-STARRS1 Medium Deep Survey

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Abstract. We conducted a systematic search for periodically varying quasars, which are predicted manifestations of sub-pc supermassive black hole binaries (SMBHBs), in the Pan-STARRS1 Medium Deep Survey (PS1 MDS). Since the normal variability of quasars can also mimic periodicity over a small number of cycles, we have extended the temporal baseline by monitoring the candidates with the Discovery Channel Telescope and the Las Cumbres Observatory telescopes. We have also adopted a more rigorous method to evaluate the significance of the periodic candidates, by considering in the light curves a "red noise" background modeled as the Damped Random Walk process. While none of the candidates can be resolved by the current pulsar timing arrays (PTAs) as individual gravitational wave sources, the Large Synoptic Survey Telescope is capable of finding more periodic candidates, some of which are likely to be detected by the PTA experiment with the Square Kilometre Array.

Keywords. quasars: individual, surveys, gravitational waves

1. Introduction

Supermassive black hole binaries (SMBHBs) should be common products as galaxies grow through mergers in the ΛCDM Universe (e.g. review by Kormendy & Ho 2013). The supermassive black holes (SMBHs) in the centers of the merging galaxies form a pair at < 10 kpc separations and can be observed as a dual active galactic nucleus (AGN) when both SMBHs are actively accreting. The binary orbit further shrinks to < 1 pc by interaction with stars and a gas disk, and gravitational wave radiation eventually drives the SMBHB to coalesce. SMBHBs at close separations are therefore also the loudest expected gravitational wave (GW) sources for the pulsar timing arrays (PTAs) in the nHz-μHz frequency band.

Many theoretical efforts have been dedicated to exploring the *indirect* observational signatures of an SMBHB. (Magneto-) Hydrodynamical simulations of an SMBHB system (e.g. MacFadyen & Milosavljević 2008; Shi *et al.* 2012; Noble *et al.* 2012; D'Orazio *et al.* 2013; Gold *et al.* 2014) find that (1) the binary torque clears and maintains a low-gas density cavity of a radius $r \sim 2a$ (where a is the binary separation) in the circumbinary disk, and material is ushered in through a pair of accretion streams; and (2) the accretion rate onto the binary is strongly modulated on the order of the binary orbital frequency for various mass ratios. Thus, for typical SMBH masses, the SMBHBs should manifest as quasars that periodically vary on the timescale of months to years, assuming the accretion luminosity directly tracks the mass accretion rate. More recently, D'Orazio *et al.* (2015) also proposed a relativistic Doppler boosting model to interpret the variability of the SMBHB candidate PG 1302–102 (first reported by Graham *et al.* 2015a), where the emission from the mini-disk of the secondary black hole is Doppler boosted as it travels at a relativistic speed along the line of sight.

There have been a number of systematic searches for periodic quasars as SMBHB candidates in optical time domain surveys — e.g. Graham *et al.* (2015a) and Graham *et al.* (2015b) in the Catalina Real-time Transient Survey (CRTS); Charisi *et al.* (2016) in the Palomar Transient Factory (PTF); and Liu *et al.* (2015), Liu *et al.* (2016), and Liu *et al.* (in preparation) in the Pan-STARRS1 (Kaiser *et al.* 2010) Medium Deep Survey (PS1 MDS) — and more than 100 SMBHB candidates have been claimed so far.

However, most of those candidates have less than $\sim 2-3$ cycles of variation, making it easy for normal, stochastic variability of AGN and quasars to masquerade as periodic sources (e.g. Vaughan *et al.* 2016). Therefore, after conducting a systematic search in PS1 MDS for periodic quasar candidates (§2), we extend the observational baseline with new imaging data taken at the Discovery Channel Telescope (DCT) and the Las Cumbres Observatory (LCO) network and adopt a more rigorous maximum likelihood method from Zoghbi *et al.* (2013) which takes into account a "red noise" background (§3). We have down-selected a sample of more robust candidates and are able to infer binary parameters from this population of SMBHB candidates. We conclude with discussions of GW detection of SMBHBs by the PTAs in §4.

2. A systematic search for periodic quasars in PS1 MDS

PS1 MDS surveyed 10 circular fields distributed across the sky, each of which is ~ 8 deg^2 in size, from 2009-2014. It observed in the g r i z y filters, the first four of which have been used in our study. Each MD field is chosen such that it overlaps with an existing extragalactic survey field. In our pilot study in the MD09 field (Liu *et al.* 2015; Liu *et al.* 2016), which overlaps with SDSS Stripe 82, we first cross-matched the $40,488$ point sources extracted from MDS with a custom catalog of deep stacks in the Canada-France-Hawaii Telescope (CFHT) u band and PS1 g r i z bands (Heinis *et al.* 2016), after applying a magnitude cut at $m < 23$ mag. We converted the magnitudes to the SDSS system and apply the color box from Sesar *et al.* (2007) and selected 670 quasars by color. We then measure the observed variability (defined as the standard deviation σ of the light curve) of each quasar and compare with that of an ensemble of nearby stars of similar brightness. As most stars are not intrinsically variable, any scatter in their light curves should only be due to photometric errors and other systematic effects and therefore establish our sensitive limit in detecting variable sources. We selected 104 variable quasars at the $> 2\sigma$ level.

Using the Lomb-Scargle periodogram (Horne & Baliunas 1986) and taking advantage of PS1 monitoring in multiple filters, we then look for a coherence periodic signal in at least three of the four filters. Among the 77 variable quasars that met this requirement, we also require a minimum signal-to-noise (> 3) and at least 1.5 cycles of variation. The search resulted in 3 periodic candidates from a ~ 5 deg^2 of PS1-CFHT cross-matched sky area (Liu *et al.* 2016).

3. Putting candidates to the test

However, stochastic variability of normal quasars and AGN, characterized by either the Damped Radom Walk model (DRW; Kelly *et al.* 2009) or a power spectral density (PSD) model of a broken power law, can easily mimic a periodic variation over a small number of cycles ($\sim 2-3$), especially with large photometric errors and sparse sampling (Vaughan *et al.* 2016). Therefore, to address the issue of "red noise" contaminating our selected sample, we have extended the baseline of observations using available archival

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light curves from the SDSS Stripe 82 survey (2000-2008) and have also been monitoring the candidates with new imaging data taken with the Large Monolithic Imager (LMI) at DCT (since 2015 May) and the Spectral imager on the LCO network telescopes (since 2017 April).

Our imaging programs on DCT/LMI and LCO/Spectral are carried out in the SDSS g r i z filters. We perform aperture photometry on the reduced images using `SExtractor` and cross-match the extracted sources with point sources from the SDSS catalog in order to convert from the `SExtractor` instrumental magnitude to an SDSS magnitude. To convert the SDSS magnitudes to the PS1 photometric system and thus directly compare with data from MDS, we calculate synthetic PS1 and SDSS magnitudes by convolving the (redshifted) composite quasar spectrum from Vanden Berk *et al.* (2001) with the respective filter sensitivity curve and then apply the magnitude offset to the LMI or LCO measurements. We then "stitched" the new measurements and SDSS Stripe 82 archival light curve with the PS1 light curve to generate an extended light curve.

We then re-ran our analysis on the extended light curves for the three candidates from MD09. None of them passed the test as persistent periodic sources, further demonstrating the importance of having long-term monitoring for candidates selected based on their apparent periodicity (Liu *et al.* 2016).

We have expanded our analysis to all 10 MD fields in Liu *et al.* (in preparation) and selected 26 periodic candidates from $9,314$ color-selected quasars. To more rigorously test their periodicity, in addition to extended baseline monitoring, we have also adopted the maximum likelihood method from Zoghbi *et al.* (2013) to re-evaluate the significance of the periodic signal in the presence of a red noise background. We model the PSD as a DRW process and search for a periodic component, which is represented by a δ-function. By comparing the likelihoods of "DRW only" and "DRW+periodic" models, we determine whether the additional periodic component is justified in both the "PS1-only" and extended light curves. We are therefore able to down-select 5 more robust candidates in which the "DRW+periodic" model is preferred (Fig. 1).

While we have directly measured quantities such as black hole mass, redshift, and variability period and have inferred a binary orbital separation by virtue of Kepler's law, we further demonstrate that it is also possible to infer or constrain other binary parameters such as mass ratio from a population of variability-selected SMBHB candidates. We compute the binary residence times $t_{\rm res}$ for the PS1 MDS candidates for a range of mass ratios $q = 0.01 - 1$ and compare the distribution with that of a population of purely GW-driven SMBHBs. After correcting for observational constraints due to the limited baseline of PS1 MDS, we find that the full sample of 26 SMBHB candidates is poorly matched to the expected $t_{\rm res}$ distribution for all mass ratio cases, while the down-selected sample is well-matched to the expected distribution for $q = 0.3$ (Fig. 2), consistent with the major galaxy merger scenario.

SMBHB candidates selected from an optical time domain survey should also be followed up with multi-wavelength observations in order to further study their observational properties; they can also provide independent evidence that could verify the binary hypothesis. In the UV and optical wavelengths, for example, Roedig *et al.* (2014) predicted that the cavity in the circumbinary disk should produce a spectral "notch", which can be probed in the SED or optical/UV spectrum of the quasar. They have also predicted that due to the accretion stream shock-heating the edge of the mini-disk, it would produce a hot spot that corresponds to a hard X-ray excess at ~ 100 keV. For SMBHB candidates at high redshifts ($z \gtrsim 1$), this unique signature is within the spectral window of *NuSTAR* ($3 - 79$ keV).

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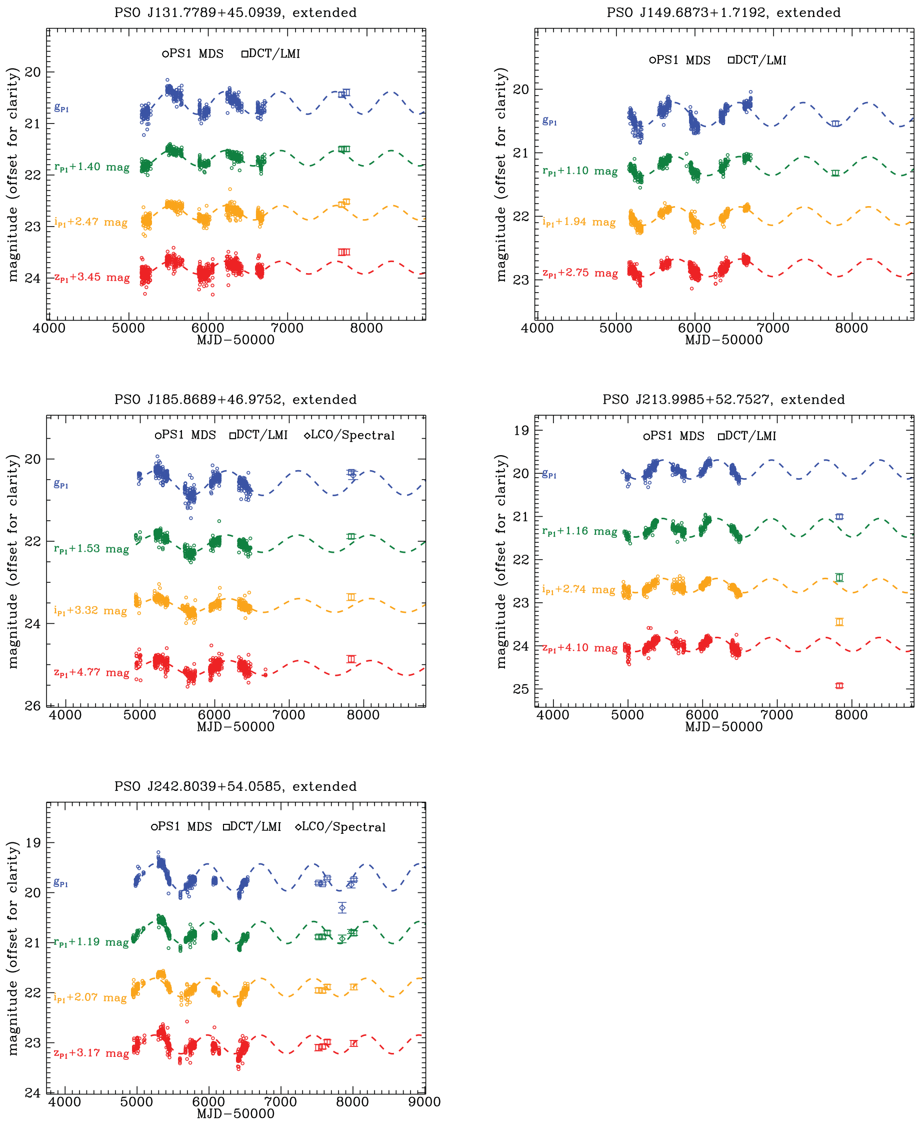

Figure 1. Five "gold" candidates from PS1 MDS in which a periodic component is present after including a DRW background Liu *et al.* (in preparation). Their g r i z band light curves from MDS (circles; photometric error bars have been omitted for clarity) are shown with new monitoring data taken with DCT/LMI (squares) and LCO/Spectral (diamonds) between 2016 May (approximately MJD 57500) and 2017 September (approximately MJD 58000). Sinusoids are fitted to the "PS1-only" light curves and have been extrapolated to guide the eye.

4. SMBHBs as low-frequency GW sources for the PTAs

The search for periodic quasars in large time domain surveys can also open up the study of them as electromagnetic counterparts of nanohertz-frequency GW sources. While none of the candidates from PS1 MDS can yet be resolved by the current PTAs based on our estimation of their binary parameters, we predict based on our benchmark study with MDS that $\sim 20,000$ periodic quasar candidates of more than 3 cycles could be detected by the Large Synoptic Survey (LSST), ~ 100 times more than the total number of currently

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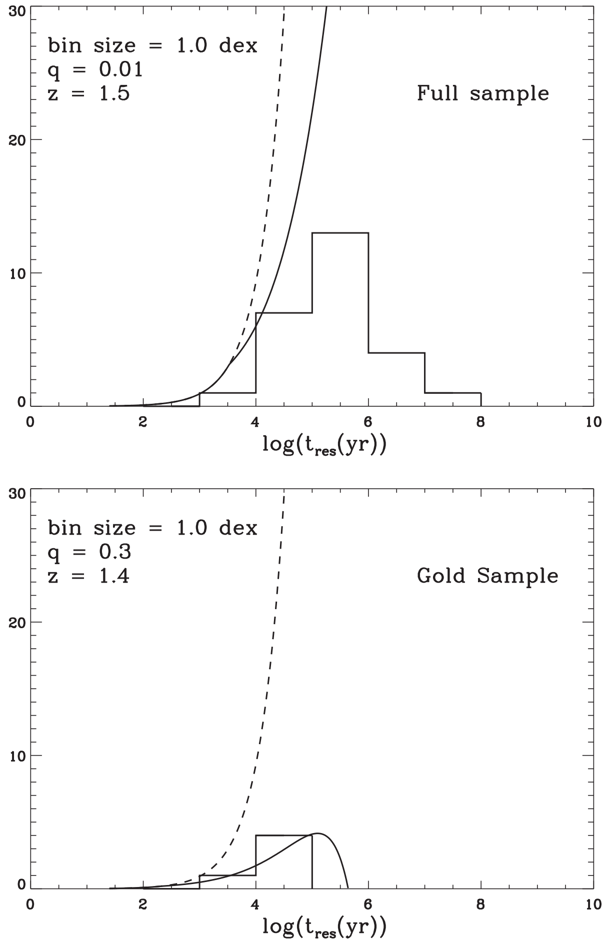

Figure 2. We calculate the expected distribution of residence times ($t_{\rm res}$) for a population of GW-driven SMBHBs (dashed curves) and compare the distribution after taking into account observational constraints (solid curves) with that of the SMBHB candidates selected from PS1 MDS (histograms). The Full sample of 26 candidates is poorly matched to the expected distribution even for an extreme mass ratio q = 0.01 (top panel), while the Gold sample of five selected after our re-analysis is in significantly better agreement with the expected distribution, if $q = 0.3$ is adopted (bottom panel) Liu *et al.* (in preparation).

claimed candidates Liu *et al.* (in preparation). Scheduled to operate for 10 years, LSST will also be able to detect periodic candidates with more cycles, thus decreasing the false alarm rate due to normal quasar variability.

Adopting the probability densities of the binary parameters of the first likely GW sources for the International Pulsar Timing Array (IPTA) and Phases 1 and 2 of the Square Kilometre Array (SKA1 and SKA2) from Rosado *et al.* (2015), we draw realizations of SMBHBs and compare with the parameter space that CRTS, PS1 MDS, or LSST is sensitive to, adopting a minimum of 3 cycles of periodic variation. While none of the current candidates from CRTS or PS1 MDS can be resolved by IPTA as individual GW sources, LSST can probe part of the GW strain-frequency parameter space accessible by SKA1 and SKA2 and thus is likely to yield the first individual GW sources for detection by the SKA (Fig. 3).

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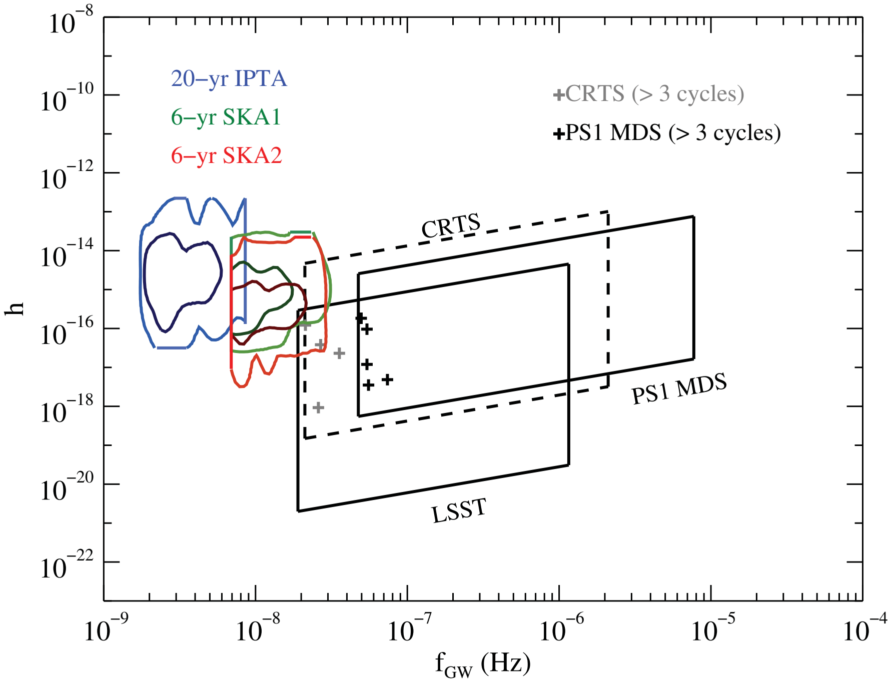

Figure 3. We show the GW frequency ($f_{\rm GW}$) and strain amplitude (h) of the SMBHB candidates from CRTS (Graham *et al.* 2015b) and PS1 MDS Liu *et al.* (in preparation) that have more than 3 cycles of variation (grey and black crosses, respectively), as well as the $f_{\rm GW}$-h parameter space that systematic searches in CRTS, MDS, and LSST are sensitive to (dashes, solid, and dotted boxes, respectively). LSST is capable of yielding SMBHB candidates that are the most likely first GW sources detectable by the SKA1 or SKA2 array.

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