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A Periodically Varying Luminous Quasar at z = 2 from the Pan-STARRS1 Medium Deep Survey: A Candidate Supermassive Black Hole Binary in the Gravitational Wave-Driven Regime

Tingting Liu and Suvi Gezari

Department of Astronomy, University of Maryland, College Park, MD 20742, USA
email: tingting@astro.umd.edu

Abstract. Supermassive black hole binaries (SMBHBs) should be an inevitable consequence of the hierarchical growth of massive galaxies through mergers and the strongest sirens of gravitational waves (GWs) in the cosmos. Yet, their direct detection has remained elusive due to the compact (sub-parsec) orbital separations of gravitationally bound SMBHBs. Here we exploit a theoretically predicted signature of SMBHBs in the time domain. We have begun a systematic search for SMBHB candidates in the Pan-STARRS1 Medium Deep Survey (MDS) and reported our first significant detection of such a candidate from our pilot study of MD09 in Liu *et al.* (2015). Our candidate PSO J334.2028+01.4075 has a detected period of 542 days, varying persistently over the available baseline. From its archival spectrum, we estimated the black hole mass of the z = 2.06 quasar to be $\sim 10^{10}$ $M_{\odot}$. The inferred ~ 7 R_s binary separation therefore puts this candidate in the regime of GW-dominated orbital decay, opening up the exciting possibility of finding GW sources detectable by pulsar timing arrays (PTAs) in a wide-field optical synoptic survey.

Keywords. black hole physics; quasars: individual

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1. Introduction

Supermassive black hole binaries (SMBHBs) are expected to form as a result of the merger of two massive galaxies in the ΛCDM Universe (e.g. Begelman *et al.* 1980). Though binaries that already evolved into the GW-driven stage ($a \ll 1$ pc) are impossible to resolve directly at cosmological distances, their potential periodic variability as an indirect observational signature has been explored theoretically. Simulations of an accreting SMBH binary embedded in a circumbinary disk show that for a mass ratio $0.05 < q < 1$ – as expected in a major galaxy merger – mass accretion through the circumbinary disk is strongly modulated by the binary's orbital motion (e.g. Gold *et al.* 2014; D'Orazio *et al.* 2013; Noble *et al.* 2012) and, in many mass ratio cases, varies on a time scale which is on the order of the binary orbital time scale, which is in turn a function of the total black hole mass and orbital separation. Assuming that luminosity tracks mass accretion of the binary, the former should then vary periodically as the latter varies.

The survey requirements to yield a statistically meaningful number of periodically varying quasars (Haiman *et al.* 2009) are an excellent match to the survey power of the Pan-STARRS1 (PS1; Kaiser *et al.* 2010) Medium Deep Survey, thus motivating our systematic search in the Medium Deep fields.

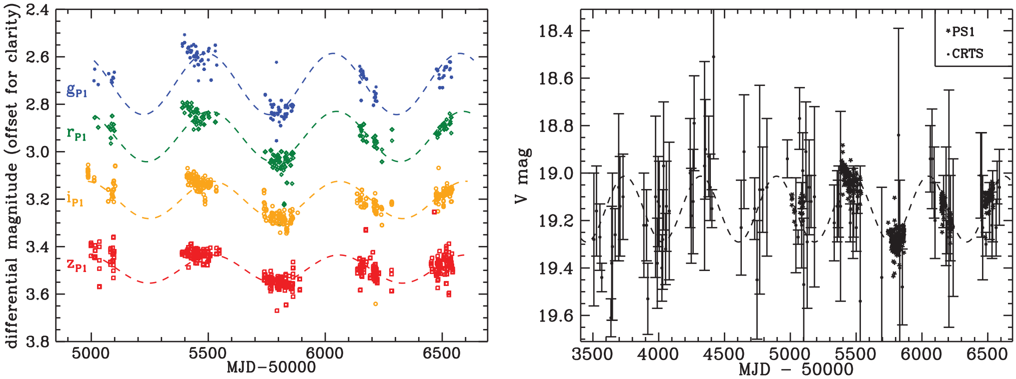

Figure 1. *Left*: Sinusoidal fit of P=542 days plotted over the candidate's complete PS1 light curves in the g, r, i, and z bands. *Right*: PS1 light curve (asterisks) converted to the V band and the archival CRTS light curve (dots with error bars). The CRTS measurements are generally consistent with the PS1 light curve and the sine fit to the PS1 light curve over 6 cycles (dashed curve) (Liu *et al.* 2015)

2. Methods and Results

In our analysis, in order to maximize our sensitivity to intrinsic variability, we first applied a precision photometry technique of differential ensemble photometry on all point sources selected in PS1 MD09. This technique locally reduces the scatter of detections due to atmospheric effects, by comparing a target object with nearby (non-variable) stars (Bhatti *et al.* 2010; Honeycutt 1992). We then identified intrinsic variables at the 2σ level compared to stars, and cross-matched them with color-selected quasars from a custom catalog of deep stacks in the g, r, i, z, y band from the full PS1 survey and in the u band from the Canada- France-Hawaii Telescope (Heinis *et al.* 2015). From this variable quasar sample, we then used the discrete Fourier transform technique of Lomb-Scargle periodogram (Horne & Baliunas 1986) to look for coherent periodicity across filters.

Our reported candidate, PSO J334.2028+01.4075, was selected as the most significant detection in our search in MD09. It has a coherent period of $\sim$542 $\pm$ 15 days in the g, r, i, and z filters from our periodogram analysis, corresponding to $\sim$3 cycles of oscillation that is well fitted to a sinusoidal function (Fig.1). It is a radio-loud quasar in the VLA FIRST catalog and has an archival spectrum from the FIRST Bright Quasar Survey (FBQS; Becker *et al.* 2001), which indicated that the z = 2.06 quasar had a rest-frame period of $\sim$177 days. From its archival FBQS spectrum, we estimated its black hole mass to be $\log(M_{BH}/M_\odot) = 9.97 \pm 0.50$, corresponding to an orbital separation of 7^{+8}_{-4} Schwarzschild radii ($0.006^{+0.007}_{-0.003}$ pc), suggesting that the candidate SMBHB system is within the regime of GW-dominated orbital decay.

We also had the benefit of testing the robustness of our periodic detection from the 4.2 yr baseline of PS1 with extended baseline photometry from archival light curve from the Catalina Real-Time Transient Survey (CRTS; Drake *et al.* 2009), resulting in a baseline totaling more than 8 years ($\sim$6 cycles), during the period of which PSO J334.2028+01.4075 showed persistent periodic behavior (Fig.1). We also plan to monitor PSO J334.2028+01.4075 with extended baseline imaging in the upcoming years. Extending the baseline of observations will break a false periodic signal and provide a robust test for our candidates.

3. Conclusions

Our successful pilot program with PS1 MD09 is a promising start of our systematic search for signatures of SMBHBs in the time domain, a novel approach with the potential to yield dozens of candidates with the entire $\sim$80 deg^2 PS1 MDS, making it possible to statistically identify a population of SMBHBs in the GW-dominated regime of orbital decay and to study the number rate of such systems as a function of the variability time scale, as predicted by theory.

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