

UPDATE IN THE SEARCH FOR CLOSE MASSIVE BINARY BLACK HOLES: A LIST OF NEW CANDIDATES

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Abstract. Supermassive black holes are found in the center of galaxies. However, their formation and evolution is still obscure. Even though they are thought to be formed from lower mass seed black holes, the merger and accretion rate of these black holes is still unconstrained. The next space-based gravitational wave observatory LISA will constrain the merger rate of massive black holes, and thus shed light on how they are formed. We conducted a search for MBBHs candidates using Catalina Real-Time Transient Survey (CRTS) and Zwicky Transient Facility (ZTF) observations. We searched for long-term sinusoidal modulation emanating from the centres of galaxies, which may be evidence of MBBHs or coming from a circumbinary disk. We found 36 MBBHs candidates. We present here the results of this study.

Keywords: Gravitational waves - Black hole physics - Catalogs - Galaxy: evolution - Galaxy: formation - quasars: supermassive black holes

1 Introduction

Observations revealed the presence of supermassive black holes ($M \sim 10^5\text{--}10^6 M_\odot$) in the center of galaxies (Vestergaard & Osmer 2009). However, their formation and evolution is still unclear. In a hierarchical model, we expect them to be created from lower mass black holes seeds, stellar ($M \sim 5\text{--}60 M_\odot$; Mapelli et al. (2020)) or intermediate ($\sim 10^2 M_\odot < M < 10^5 M_\odot$; Greene et al. (2020)) mass black holes. These seeds may evolve through different processes, periods of intense accretion and/or successive mergers (Volonteri et al. 2003). The importance of these two scenarios and when they dominated is still obscure. As two galaxies merge, when the orbital separation is sufficiently small, the inspiral of the two supermassive black holes generates gravitational waves. The next space-based gravitational waves observatory LISA (Laser Interferometer Space Antenna) will be able to probe the milli-hertz regime of the gravitational wave spectrum (Amaro-Seoane et al. 2017). Massive binary black hole (MBBHs) of mass $M \approx 10^4\text{--}7 M_\odot$ are expected to be loud mHz gravitational wave sources. LISA will detect these objects up to a redshift $z \sim 20$ (Amaro-Seoane et al. 2012) and thus, this will bring constraints on the evolutionary paths of supermassive black holes. Numerical simulations showed that when the binary hardens, mini-disks around each black hole are created and a circumbinary disk forms at a radius $r \sim 2a(1+e)$, with a and e respectively the semi-major axis and eccentricity of the binary. A cavity is established between the circumbinary disk and the mini-disks, accretion streams coming from the circumbinary disk cross the cavity to fuel each mini-disk (d'Ascoli et al. 2018; Shi & Krolik 2015; Combi et al. 2021). Therefore, we expect to detect long-term sinusoidal modulation either from the orbiting mini-disks or from a blob of matter in the circumbinary disk. Mignon-Risse et al. (2023) showed that an over-density can grow in the circumbinary disk which could explain the observed variability. This variability could also come from periodic accretion flow, as the lower mass black hole in the orbit is closer to the inner edge of the circumbinary disk, more gas is accreted by the secondary black hole (Artymowicz & Lubow 1996). Another origin for this variability is periodic Doppler boosting, as the two black holes orbit, the light emitted from the mini-disks is periodically boosted (D'Orazio et al. 2015). Sub-parsec scale orbital separation MBBHs are still to be confirmed and only candidates have been proposed. Graham et al. (2015) made a systematic search for long-term optically variable objects in the Catalina Real-Time Transient Survey (CRTS) and reported 111 quasars that could harbor a MBBH. Nevertheless, quasars exhibit an intrinsic optical variability due to the turbulent accretion process in

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such systems. This variability is well modelled by a red noise process and, as described in Vaughan et al. (2016). It is therefore necessary to observe a sufficient number of periods to ensure that the periodicity is caused by an orbital motion and not due to a stochastic modulation. So as to verify that the periodicity of the candidates discovered by Graham et al. (2015) is sustained over enough periods, we added Zwicky Transient Facility (ZTF) observations, when available, to the CRTS lightcurves. Additionally, we searched for other candidates using both CRTS and ZTF data. CRTS observations were made between 2005 and 2015 in the V-band using three telescopes, respectively the Mt Lemmon Survey, Catalina Sky Survey and Siding Spring Survey. The CRTS catalog contains around 500 million objects and covers nearly 26000 square degrees in the northern sky (Drake et al. 2009). ZTF observations debuted in 2017 and are still ongoing. They are performed at the Palomar observatory in r, g and i filters. The ZTF catalog is much bigger than CRTS and includes around 7 billion objects located in 30000 square degrees in the northern sky (Bellm et al. 2019).

2 Methods

We extended the lightcurves of sources with CRTS only data shown in Graham et al. (2015) adding ZTF observations when available. Also, we investigated the Chen et al. (2020) list of variable sources to search for sinusoidal modulation. This catalog contains 2 163 129 objects detected with the Zwicky Transient Facility (ZTF) Data Release 2 (DR2). Firstly, we cross-correlated this catalog with Glade2, a galaxy catalog, which includes 3.26 million galaxies and quasars. This catalog is complete to a luminosity distance of 37 Mpc (Dályá et al. 2018). We extracted ZTF DR16 lightcurves of galaxies and kept the ones with at least 400 ZTF measurements to ensure reliable statistical results. We grouped data points into bins of 4 days and modelled a sinusoidal function to test the variability of the lightcurves. We then calculated the reduced chi-squared to evaluate the goodness of the fit. We selected objects for which the value of the reduced chi-square was lower than 1.3. Where CRTS data was available for the ZTF variable sources, we also added it to the lightcurves to extend the baseline, and selected the ones with at least 25 data points after binning to limit stochastic effects. However, CRTS observations were made in the V band whilst ZTF observations were done in r, g and i filters making it difficult to model both data sets simultaneously. As we are interested in the timescale of the variability and not its amplitude, we scaled ZTF observations to the CRTS data using the average magnitude and amplitude of the CRTS variability, as we assume the periodicity to be achromatic. After scaling ZTF observations to CRTS data, we fitted a sine function to the ZTF and CRTS data sets altogether. To find the best fit, we used the nested sampling package Ultraneest (Buchner 2021b,a, 2016) to derive posterior probability distributions of the sinusoidal model. This method evaluates the posterior distribution by calculating the marginal likelihood Z over the whole parameter space. In order to further validate the identified periods determined through the fitting techniques, we also computed the Lomb-Scargle periodogram. The Lomb-Scargle is a technique to find periodicities in irregularly sampled observations (Lomb 1976; Scargle 1982). This technique calculates the Power Spectral Density (PSD) for a given data set, where most likely periods in the observations are represented by the highest peaks in the PSD. Moreover, to evaluate the peak significance we calculated the false alarm level for each periodogram. This corresponds to the minimum power a peak must reach to be considered significant for a given confidence interval. We computed the 5σ false alarm level and only considered peaks above this threshold.

3 Results

3.1 Lightcurves

We searched for interesting candidates in the Graham et al. (2015) sample. We found ZTF observations for 89 objects out of the initial 111 sources. We modelled CRTS and ZTF data simultaneously and recognized 26 candidates with a similar variability in both CRTS and ZTF observations. We discarded 58 candidates as the variability observed in CRTS data was inconsistent with the one in ZTF observations. Finally, there were not enough ZTF observations for 5 sources to confirm that the modulation continued on the long-term. Additionally, we investigated the Chen et al. (2020) catalog and cross-matched it with the galaxy catalog Glade2 (Dályá et al. 2018), reducing the sample to 21 862 galaxies. We fitted ZTF data and selected sources with a $\chi^2_\nu < 1.3$, identifying 1010 variable galaxies. We found 10 objects with analogous modulations in CRTS and ZTF data. The calculated Lomb-Scargle periodogram for each of the 36 selected candidates exhibit a maximum peak corresponding to the periodicity of the best fitted sine function, supporting the proposed variability. We show in 1 the optical lightcurve and Lomb-Scargle periodogram of one of the candidates.

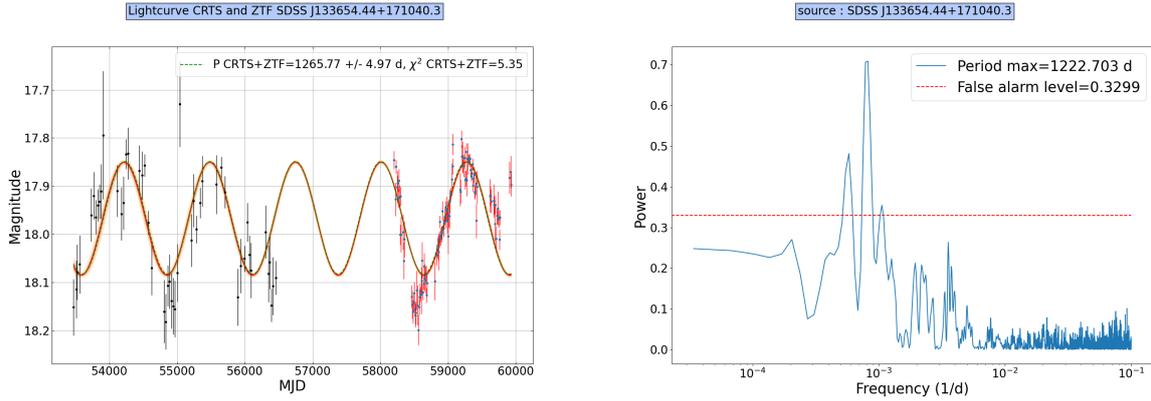


Fig. 1. Left: CRTS (black) and ZTF (red) optical lightcurve of one of the 36 candidates : SDSS J133654.44+171040.3. Orange line is 3σ best fitted sine function **Right:** Lomb-Scargle periodogram of SDSS J133654.44+171040.3 panel.

In our final sample of 36 candidates, we observe between 3 and 5 periods, which may indicate the presence of a MBBH in these galaxies. Moreover, out of the 1099 sources we inspected (1010 from Chen et al. (2020) catalog and 89 from Graham et al. (2015) sample), we focused our study on objects with both CRTS and ZTF data, and objects with too few or no CRTS observations have been removed from our final sample. Insufficient cycles are available in the current data to confirm the modulation, but 261 objects merit further follow-up to confirm the modulation. We therefore provide a second catalog of proposed candidates.

3.2 Optical Spectra

We investigated the SDSS optical spectra when available of the sources we identified as MBBH candidates. MBBH candidates are expected to display double-peaked emission lines, due to the accretion around the two black holes, each having their own broad-line (BL) and narrow-line (NL) regions (Begelman et al. 1980; De Rosa et al. 2019). However, this is not an indisputable way to confirm MBBH candidates as it may be due to a recoiling supermassive black hole (e.g. Komossa et al. 2008) or a background AGN (e.g. Heckman et al. 2009). Nonetheless, observing both long-term sinusoidal variability and double-peaked emission lines lends weight to the MBBH scenario. One of the objects in our sample of MBBHs candidates seems to have double-peaked emission lines in its optical spectra. We show in Fig 2 the SDSS optical spectra of quasar SDSS J122616.70+504205.9 with identified double-peaked $H\beta$ and Mg_{II} emission lines. This may indicate that this source possesses two BL regions and further support the idea that this galaxy may host a MBBH.

4 Conclusions

We report 36 MBBHs candidates through the identification of 3 to 5 periods of sinusoidal variability in their optical lightcurve. These periodicities have been found using a fitting technique and confirmed by their Lomb-Scargle periodogram. In this work, we also could reject 58 objects previously proposed as MBBHs candidates, because the observed variability in CRTS observations was not sustained in later ZTF data. Additionally, we investigated the SDSS optical spectrum of these candidates and found double-peaked emission lines for one candidate, favoring the MBBH hypothesis. Also, we created a catalog of possible MBBH candidates which require further follow-up observations to confirm the long-term sinusoidal modulation. Upcoming surveys, such as the Rubin observatory Legacy Survey of Space and Time (LSST, Ivezić et al. 2019), will help us to confirm or discard current MBBHs candidates and discover many more of them.

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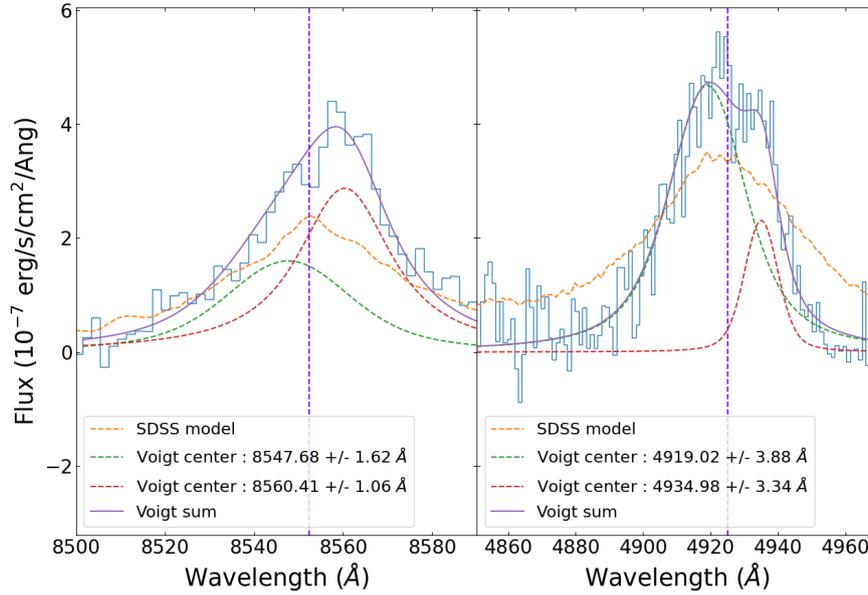


Fig. 2. Normalized flux of identified double-peaked emission lines H_{β} (left) and Mg_{II} in SDSS optical spectra of quasar SDSS J122616.70+504205.9

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