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ASTROPHYSICAL JOURNAL, 859(1)

0004-637X

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2018-05-20

10.3847/1538-4357/aab3c5

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Peer reviewed
No Evidence for Periodic Variability in the Light Curve of Active Galaxy J0045+41

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ABSTRACT

Dorn-Wallenstein, Levesque, & Ruan recently presented the identification of a \( z = 0.215 \) active galaxy located behind M31 and claimed the detection of multiple periodic variations in the object’s light curve with as many as nine different periods. They interpreted these results as evidence for the presence of a binary supermassive black hole with an orbital separation of just a few hundred AU, and estimated the gravitational-wave signal implied by such a system. We demonstrate that the claimed periodicities are based on a misinterpretation of the null hypothesis test simulations and an error in the method used to calculate the false alarm probabilities. There is no evidence for periodicity in the data.

Keywords: galaxies: nuclei — galaxies: active — quasars: general — quasars: individual (2MASS J00452729+4132544)

1. INTRODUCTION

It is generally expected that binary supermassive black holes should form in the aftermath of galaxy mergers, but direct evidence for close (sub-pc separation) binary black holes in galaxy nuclei remains elusive despite much observational effort. One possible way to identify binary black holes is to search for quasars or active galactic nuclei (AGN) exhibiting periodic variations in brightness that might be associated with the binary orbital period. Periodic flux variability may be expected as a result of the interaction between the binary and a circumbinary accretion disk (e.g., MacFadyen & Milosavljević 2008; Haiman et al. 2009), or through periodic modulation caused by relativistic boosting of emission from gas bound to the lower-mass secondary black hole in an unequal-mass binary (D’Orazio et al. 2015).

Over the past few years there have been numerous claims for periodic flux variations in AGN identified through searches of large samples of AGN light curves obtained in time-domain surveys (Graham et al. 2015a,b; Liu et al. 2015, 2016; Charisi et al. 2016). Genuine periodic flux variability in AGN is apparently extremely rare, and it is debatable whether any objects have yet shown compelling evidence of light curve periodicity, but the number of candidates is growing rapidly. False positive detections of periodicity are a serious risk, because random, aperiodic AGN variability can sometimes produce repeated up-and-down variations that can easily be mistaken for periodicity, particularly when only a few cycles are seen in the data (Vaughan et al. 2016). However, once candidates are identified, further long-duration monitoring can determine whether the periodicity is likely to be real or not. To test the significance of any possible periodicity identified in an AGN light curve, it is essential to carry out careful Monte Carlo simulations to estimate the false positive rate: that is, the probability that a suitably chosen stochastic variability process will produce a periodicity signal at least as strong as that found in the data.

Recently, Dorn-Wallenstein et al. (2017, hereinafter DLR) presented the identification of a previously unknown AGN, J0045+41. This object appears within the disk of M31 as projected on the sky, and has been classified in the past as an M31 globular cluster or globular cluster candidate (e.g., Galleti et al. 2004).¹ DLR examined the X-ray spectrum of J0045+41 and obtained an optical spectrum showing that the object is actually a broad-lined AGN at \( z = 0.215 \). They also reported the detection of multiple periodicities in the object’s optical light curve with the strongest periodicity at 354.84 days, and interpreted the results as evidence for a binary supermassive black hole with an orbital separation of just a few hundred AU.

Given the rarity of periodicity in AGN and the importance of identifying binary black holes, the claim of compelling evidence for multiple periodicities in J0045+41 by DLR should be examined carefully. If correct, it would be a remarkable discovery, and if this object were even merely a promising candidate for periodic variability it would merit extensive follow-up observations to verify or rule out the periodicity. The purpose of this paper is to show that the claims of periodicity in J0045+41 are unfortunately not valid. The periodicities are spurious, arising from a combination of incorrect

¹ This object appears in the SIMBAD catalog as 2MASS J00452729+4132544. In NED, it is listed under the designation CXO J004527.3+413255. Kim et al. (2007) identified it as a “possible” globular cluster in M31, but noted that some of the possible clusters in their sample might actually be background galaxies. Assuming the globular cluster identification for this object, Maccarone et al. (2016) interpreted the associated X-ray source as an X-ray binary, based on observations from NuSTAR and Swift.
interpretation of null hypothesis simulation tests and an incorrect calculation of the false alarm probability.

2. EVALUATING THE EVIDENCE FOR PERIODICITY

DLR use g-band light curve data from the Palomar Transient Factory (PTF) to search for periodicity in this object. The light curve is shown in their Figure 7. It is immediately apparent that the light curve is very noisy and sparsely sampled with large seasonal gaps. The data points and error bars in the plot are so crowded together that it is difficult to see most of the individual points. DLR do not list the light curve data in a table, nor do they give any quantitative information about the uncertainties on the data points, and at present only a portion of this light curve is available in the PTF public archive. Nevertheless, it is clear from inspection that both the AGN variability amplitude and the S/N of the light curve are rather low. There is a gradual increase in the source brightness over the 6-year monitoring duration, with the last three monitoring seasons having a slightly higher mean brightness (by perhaps \( \sim 0.25 \) mag) than the earlier seasons. From the outset, it is unlikely that data of this quality would be sufficient to demonstrate any periodicity to high significance, let alone multiple periodicities. PTF r-band data are also presented, with higher S/N than the g-band data, but they primarily consist of just two monitoring seasons and the r-band light curve does not appear to show any obvious variability.

To measure the periodogram of the g-band light curve, DLR use an algorithm that employs a non-parametric periodic model rather than the common approach of using a sinusoidal model (e.g., Graham et al. 2015b; Charisi et al. 2016; Liu et al. 2016). The periodogram is sampled on a uniform grid of 2000 trial periods ranging from 60 to 1000 days. As shown in their Figure 8, they find a trend of rising power \( P \) at longer timescales, but with irregular peaks and troughs in the plot of \( P \) versus period \( T \). Such features can occur due to the sampling cadence of the light curve rather than the variability power of the AGN itself. The important question is whether any of the peaks represent power significantly above what might be expected due to the ordinary stochastic variability of an AGN. This requires Monte Carlo simulations to test the null hypothesis, which in this case is the hypothesis that the observed periodogram power can be generated by an aperiodic variability process.

To perform this test, DLR carry out simulations in which they generate mock light curves following a damped random walk (DRW) process with DRW parameters selected to match those of the observed light curve, then resample the light curves and add noise to match the cadence and S/N of the data, and then measure the periodogram of each simulated light curve. In itself, this is a standard and reasonable approach to carrying out null hypothesis simulations (with a few caveats mentioned at the end of this section). The results of the DRW simulations are illustrated in the left panel of their Figure 10, which compares the periodogram of the data with that of the simulations, plotted as the mean DRW periodogram and a \( \pm 1\sigma \) confidence band around the mean based on the distribution of power at each period in the simulated periodograms.

This plot shows that the periodicity power in the data is within or below the \( 1\sigma \) confidence band of the DRW simulations at nearly all the trial periods ranging from 60 to 1000 days. There is only one narrow peak where the data power exceeds the \( 1\sigma \) confidence band of the simulations, corresponding to the claimed \( \sim 355 \) day period. However, a feature extending to slightly above \( 1\sigma \) in a small range of adjacent period bins (out of 2000 periods searched) could presumably arise very easily by chance in an aperiodic DRW light curve. When searching for a possible periodicity signal over a broad range of periods without a priori knowledge of where the periodicity might lie, the look-elsewhere effect comes into play (e.g., Gross & Vitells 2010), and a peak would have to be a very strong outlier extending far above the \( 1\sigma \) confidence band of the simulations in order to have a chance of being truly significant. For the J0045+41 light curve, since the level of power over the entire period search range can evidently be reproduced by typical simulations of stochastically variable light curves, the most straightforward interpretation of the null hypothesis test simulations is that there is simply no evidence of periodicity.

Despite the fact that there is only one peak exceeding the mean power level of the DRW simulations by more than \( 1\sigma \) (and only by a small amount), DLR claim to detect evidence of nine separate periodicity peaks in the data. To test quantitatively whether a claimed peak in the periodogram is significant or not, the simulation results can be used to calculate the expected false positive rate or false alarm probability (FAP). The FAP essentially gives a p-value for the null hypothesis, that is, the probability that the aperiodic DRW simulations can produce a periodogram peak as great or greater than one seen in the data. DLR calculate the FAP in the following way. The total number of DRW simulations performed is \( N_{\text{DRW}} = 96,000 \). They first rebin the periodogram into \( N_{\text{trial}} = 100 \) period bins containing 20 periods per bin. Within each bin, they find the highest value of the periodogram power in the data signal \( \{ \text{power } P_{\delta}(T) \text{ at period } T \} \), and then determine the number of simulated DRW periodograms that exceed \( P_{\delta}(T) \) within that period bin; this quantity is called \( N_{\text{DRW}}(> P_{\delta}(T)) \). The ratio \( N_{\text{DRW}}(> P_{\delta}(T))/N_{\text{DRW}} \) then gives the fraction of all simulations that exceed the data power within that period bin, i.e., a local p-value for that particular bin. To account for the look-elsewhere effect, DLR divide this ratio by \( N_{\text{trial}} \), calculating the FAP as

\[
\text{FAP} = \frac{N_{\text{DRW}}(> P_{\delta}(T))}{N_{\text{DRW}} \times N_{\text{trial}}}. \tag{1}
\]

However, this is not a correct method to calculate the FAP. The nature of the look-elsewhere effect is that the true FAP

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2 The amount by which the 355 day peak exceeds the \( 1\sigma \) confidence band of the simulations is not listed in the text of the paper and cannot be determined accurately from the figure, but it appears to be only slightly larger than a \( 1\sigma \) deviation from the mean DRW power.
must be greater than the \( p \)-value calculated by considering just the single bin where the peak is found in the data, given the presence of many other possible period bins where a DRW simulation could randomly generate a periodogram peak. Dividing by \( N_{\text{trial}} \) in Equation 1 makes the derived F AP 100 times smaller than the local \( p \)-value calculated from the single bin in which a peak is found, and it will always yield \( F \text{ AP} \leq 0.01 \) in every period bin, even in the extreme case of a bin in which every simulation exceeds the periodogram power of the data. The premise of dividing the single-bin \( p \)-value by \( N_{\text{trial}} \) to account for the look-elsewhere effect is fundamentally incorrect, and this error leads to an enormous overestimate of the significance of the putative periodicities.

How should the F AP be determined for a candidate peak in the data? Since there is no \textit{a priori} information on where a peak might be found in the periodogram, calculating the F AP essentially amounts to determining the fraction of the randomly generated simulations having power at \textit{any} period that would appear to be at least as significant as the observed peak. In other words, the F AP is a global \( p \)-value for the putative peak. If the noise level of the simulated periodograms were uniform across the full range of trial periods, then this would simply require finding the fraction of all simulations that reach power levels at least as high as the observed power of the candidate peak. However, the noise level in the simulated periodograms is strongly period-dependent. In this situation, the global \( p \)-value cannot be determined by using a uniform power threshold across all possible periods. Instead, it is necessary to examine the distribution of simulated power at each trial period. Let \( p_{\text{peak}} \) be the local \( p \)-value of the candidate peak, equal to the fraction of simulations that exceed the data power in the period bin where the peak is found. Then, in each other period bin, a fraction \( p_{\text{peak}} \) of the simulations will locally appear to have power at least as significant as that of the candidate peak. Let \( N_{\text{sig}} \) be the number of simulations that reach this significance threshold in at least one period bin, and \( N_{\text{tot}} \) be the total number of simulations performed. The F AP or global \( p \)-value is then \( N_{\text{sig}}/N_{\text{tot}} \). This method ensures that the F AP will be greater than or equal to the \( p \)-value calculated from the single bin where the peak is found, as required. As an additional check, the F AP can be recomputed using a range of possible bin widths for the periodogram, to test whether the derived F AP is sensitive to the choice of period bin size.

The results of the incorrect F AP calculation are listed in Table 1 of DLR and Equation 1, it is evident that for the strongest claimed peak at \( T \approx 355 \) days, the single-bin \( p \)-value is 0.10, meaning that 10% of the DRW simulations exceeded the periodicity power in the data within the period bin where the peak was found. The look-elsewhere effect guarantees that the actual F AP must be substantially greater than 0.10, so the null hypothesis is a very plausible explanation for the observed power in this peak. This conclusion is in stark contrast to the results of DLR, who found F AP = 1.0 \times 10^{-3} for this peak using the incorrect Equation 1. For the other peaks, the single-bin \( p \)-values range from 0.33 to 0.78, strongly contradicting the notion that these might be significant peaks. While we cannot determine the actual false positive rates for these peaks without the full DRW simulation results or carrying out new null hypothesis simulations, the simulation results presented by DLR are already sufficient to demonstrate that there is no good evidence for periodicity at all. The F AP values listed in Table 1 of DLR are too low by at least a factor of 100 in every case.

In Figure 12, DLR show phase-folded light curves that illustrate six of the identified periods. Examination of these plots gives a clearer understanding of how these spurious periodicities arise as a result of the sparse temporal sampling of the data and an aliasing effect exacerbated by the large amount of freedom in the shape of the phase-folded light curves. The “supersmooth” periodogram algorithm used by DLR allows for somewhat arbitrarily shaped bumps and kinks in the phase-folded light curves, in contrast to the smooth and regular variability of a sinusoid. Given this freedom to generate light curves of almost any shape, the period-finding algorithm is finding apparent periodicities for which the lower-flux data points from early in the campaign and the higher-flux data points from late in the campaign are almost entirely segregated in phase from each other. For example, in the phase-folded light curve for the \( T \approx 355 \) day period

\[ 10 \] 3 \text{ Table 1 of DLR lists the derived periods for these peaks to five significant figures (e.g., 354.84 days, or an implied precision of } \sim 14 \text{ minutes), but they do not give uncertainties on the periods.}
(which is claimed to be the strongest periodicity), phases 0.0–0.4 are dominated by photometry from the first half of the campaign while phases 0.5–0.9 are dominated by photometry from the second half of the campaign. This makes the phase-folded light curve appear to show that phases 0.0–0.4 have lower flux than phases 0.5–0.9, when the actual underlying behavior is that the AGN had lower flux during the first three years and higher flux during the final three years of monitoring. Furthermore, the strongest individual feature in the phase-folded light curve is a cluster of points between phases 0.8 and 0.9 (shown in light green) that were all obtained in a single year’s observations. This feature represents a single, brief brightening event in the AGN light curve with no evidence that this feature was periodic or recurring in any other year. This cannot in itself give useful evidence for periodicity. A convincing period detection would require data points from different observing seasons in the light curve to be more thoroughly mixed in phase, such that a variability feature could be clearly seen to repeat over multiple cycles. The same considerations apply to all of the phase-folded light curves for the various putative periods, which show similar phase segregations between the early (low-flux) and late (high-flux) points in the light curve. All of these false periodicities would be easily excluded by a correctly implemented FAP calculation.

Two additional points made by Vaughan et al. (2016) bear repeating here. First, there is evidence that the DRW model is not a perfect description of AGN variability, particularly on short timescales. For example, high-quality Kepler light curves (Mushotzky et al. 2011) demonstrate power spectrum slopes of $\alpha \sim -2.6$ to $-3.3$ (for $P \propto f^\alpha$ where $f$ is the temporal frequency of variations), steeper than the $\alpha = -2$ high-frequency behavior of a DRW, and this difference could lead to an overestimate of the significance of a periodicity signal if the data were compared only with DRW simulations. Ideally, in a case where evidence for periodicity appears strong, simulations should be carried out against a realistic range of power spectral shapes using the method of Timmer & Koenig (1995), or other more flexible variability models such as the CARMA model (Kelly et al. 2014). Second, an accurate assessment of the light curve uncertainties is very important. If the magnitude uncertainties on light curve data points are overestimated, this will lead to injection of too much white-noise variability into the simulated light curves when simulated data points are adjusted to account for measurement errors. This would also tend to give an overestimate of the periodicity significance.

DLR’s search for periodicity in J0045+41 was motivated by the suggestion of a 76-day periodicity in $B$ and $V$-band light curves reported by Vilardell et al. (2006) as part of a search for eclipsing binaries in M31. The Vilardell et al. (2006) data are very sparsely sampled, having been obtained in one observing run per year over a five-year duration, with each observing run spanning 3–5 consecutive nights. Such sampling is not at all sufficient to detect a 76-day period. Their phase-folded light curve (also reproduced in Figure 13 of DLR) clearly demonstrates strong variability over the five monitoring seasons with an amplitude of $\sim 1$ mag in the $B$ band. In the phase-folded light curve, the data points are grouped into five widely separated groupings in phase with large gaps between them. The explanation for the derived periodicity at $T \approx 76$ days is simply that these five groupings correspond to the five observing runs spread over five years. The AGN varied significantly from year to year, and the period-finding algorithm just rearranged the five yearly groups of data points in a way that resembled one period of a quasi-sinusoidal cycle. Almost any AGN light curve, even one that was monotonically increasing in flux over 5 years, could be rearranged to appear as though it were periodic in a phase-folded light curve if it were sampled with this extremely sparse cadence. Vilardell et al. point out this aliasing issue in their paper, noting that periodicities greater than five days in their sample are unlikely to be real. There is no reason to interpret the Vilardell et al. (2006) data as providing any evidence of periodicity at all, particularly after the object was correctly identified as an AGN by DLR.

DLR also discuss a newly obtained Gemini-N optical spectrum of J0045+41 as providing possible corroborating evidence for a supermassive black hole binary. The broad Balmer lines are asymmetric with higher flux in the blue wing, and DLR characterize the line asymmetry in terms of a Gaussian component blueshifted by $\sim 4800$ km s$^{-1}$ with respect to the systemic component. They interpret this velocity offset as possibly suggestive of a supermassive black hole binary, an outflow, or a hot spot in the accretion disk of a single supermassive black hole. For comparison, it has long been known that a subset of AGN exhibit broad-line asymmetries or velocity offsets similar to that seen in J0045+41. These sources are generally interpreted as being members of the class of double-peaked emitters, whose line profiles are well modeled as originating from an asymmetric Keplerian accretion disk around a single black hole (Eracleous & Halpern 1994; Strateva et al. 2003). There is ongoing interest in using broad-line asymmetries or double-peaked structure as potential signatures of supermassive black hole binaries (e.g., Shen & Loeb 2010; Nguyen & Bogdanović 2016; Runnoe et al. 2017), but there is not yet any direct evidence implicating binarity as the

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4 The Vilardell et al. (2006) phased light curve is available in the CDS VizieR online catalog associated with their paper, and object J0045+41 is object 3571 in their catalog of variable stars (their Table 4). The object is not mentioned in the text of their paper, presumably because they did not consider it a significant detection of periodicity. They note that “it is clear that many of the period determinations are just an alias introduced by the window function, especially for those over five days.” Among the variable objects listed in Table 4 of Vilardell et al., having apparent periods greater than five days, 39% have listed periods between 75 and 90 days, illustrating that the window function of their observations leads to numerous spurious periodicities in this range. DLR also state that Vilardell et al. classified J0045+41 as an eclipsing binary, but this is not the case. While Vilardell et al. found this object as part of a search for eclipsing binaries, it is not listed with any classification in their tables. Objects identified as eclipsing binaries or Cepheids are listed as such in their Table 4, but these amount to only 22% of their sample of 3964 variable objects, and the majority of the variable sources were not classified.
underlying cause for any observed line-profile features in AGN. While somewhat unusual, the Hα profile asymmetry in J0045+41 is not particularly extreme, and it can plausibly be understood within the context of well-established models for AGN broad-line emission without the need to invoke a supermassive black hole binary.

3. CONCLUSIONS

For all of the reasons described above, J0045+41 should not be considered as a periodically varying AGN, or even as a candidate for a periodically variable AGN based on the available data. The false alarm probabilities given by DLR are underestimated by at least a factor of 100 for all of the claimed periodicities. The data and the null hypothesis simulations do not demonstrate any evidence of periodicity whatsoever. In light of these conclusions, there is no reason to consider this object as a candidate binary black hole or to speculate about the purported binary’s orbital parameters or the anticipated gravitational-wave strain, as discussed in Section 5 of DLR.

There has been increasing effort devoted to finding binary black holes in AGN in recent years, including searches for periodic variations in photometric light curves and in the radial velocity shifts of broad emission lines. Finding even one object exhibiting compelling evidence for a binary supermassive black hole would be an exciting discovery. The increasing level of attention devoted to binary black holes following the detection of stellar-mass black hole mergers with LIGO (Abbott et al. 2016) will undoubtedly increase the motivation to identify binary supermassive black holes, and upcoming time-domain surveys including ZTF and LSST will provide a treasure trove of data in which to search for periodically varying AGN that may be candidate binaries. Well-sampled light curves with long durations and high S/N will be the key to determining whether genuinely periodic AGN can actually be found.

However, as emphasized by Vaughan et al. (2016), there is a real risk of finding false periodicities in time-domain data. It is easy for a stochastic red-noise process to mimic a few cycles of periodic variability, and searches for periodic AGN must take great care to avoid false detections. This is true even when well-sampled, high-S/N data are available. Any claims of periodicity must be viewed with skepticism, and provisionally accepted only if it can be demonstrated that the putative periodicity is extremely unlikely to have arisen by chance in a stochastic variability process. False periodicity detections can lead to a variety of negative consequences, including misdirected investments of telescope time and human effort in following up spurious results, erroneous inferences for the expected black hole merger rate and gravitational-wave event rates, and incorrect results being disseminated to the public through news releases. The case of J0045+41 provides yet another reminder of the necessity of carrying out well-designed, reproducible tests that have the capability to falsify an incorrect hypothesis. Careful attention to these issues will help future authors (and referees) to be better equipped to resist the siren call of false periodicities.

Research by A.J.B. is supported in part by NSF grant AST-1412693. The work of DS was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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