Testing the coherence of periodicity in supermassive black hole binaries

Radicati WAVE Fellowship - Final Report

Alice Heranval, *Mentor: Dr. Matthew Graham*

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Herein we present the work completed during the 2024 WAVE Fellowship and final results. Supermassive black hole binaries (SMBHBs) occur in active galactic nuclei (AGN), and emit low-frequency gravitational waves (GWs) that will be observable by the Laser Interferometer Space Antenna (LISA). However, at separations small enough to emit detectable GWs, these binaries cannot be resolved optically. Periodicity in electromagnetic emissions from AGN has been linked to the presence of SMBHBs, but it can be misleading due to the presence of stochastic noise. We aim to identify strong SMBHB candidates by studying coherence times for periodicity in both simulated and real light curves from AGN with the intention of using them to separate real signals from noise.

1 Introduction

Every massive galaxy is home to one or more SMBHs, which live in the galactic nucleus. AGN occur when these massive objects accrete neighboring gas and dust, which have too much angular momentum to simply fall into the black holes and must instead orbit the source, thereby forming an accretion disk. Within the accretion disk, gravitational potential energy is converted into often extreme electromagnetic radiation through viscous forces and friction between particles.

Massive galaxies are built up through galaxy mergers, which can also trigger AGN. While observations of dual AGN in early merger stages have been made, at sub-parsec separations it is impossible to resolve SMBHBs through direct observation, so it falls through other methods to detect them ([1]).

When compact objects such as black holes or neutron stars become gravitationally bound, the theory of General Relativity predicts that since highly massive objects cause nonlinear curvatures of spacetime, these binary systems will inspiral toward one another and eventually merge as they lose energy in the form of GW radiation. GWs are ripples in spacetime traveling at the speed of light analogous to electromagnetic radiation. When they propagate from astrophysical events such as the merger of two black holes, the resultant distortion of spacetime can be measured as the strain δ L/L in a Michelson interferometer. With the first detection of a GW by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 2015 [2], GWs were observationally confirmed. Their observation and study has since expanded globally, and 90 detections have been catalogued since the first [2, 3, 4, 5]. GWs detectable by LIGO are limited, however, to higher-frequency GWs from stellar-mass black hole mergers rather than their supermassive counterparts. Evidence of a stochastic background of GWs consistent with SMBHB mergers is given by pulsar timing arrays, which observe the arrival times of radio pulses from millisecond pulsars and measure disturbances caused by low-frequency GWs [6]. To directly observe SMBHB mergers in ranges of 0.1mHz - 1Hz, the Laser Interferometer Space Antenna (LISA) is a much larger GW observatory made up of three spacecraft currently predicted to reach completion in 2035 [7]. To study these sources before their detection through GW means, and to launch multimessenger studies when GW detection is possible, it becomes necessary to find other methods to detect these SMBHBs. Identifying strong SMBHB candidates will allow us to study them to better understand the physics that occur within the accretion disk when binaries are present, and how the emissions from AGN are affected. We will also be offered a solution to the final parsec problem, learning what happens to these binaries when they are close enough to merge. Finding strong SMBHB candidates will also help indicate the population of binaries throughout our universe and provide an estimation of the expected detection rate with LISA.

Systemic searches identify AGN from the variability in their highly redshifted light curves from stochastic noise processes in the accretion disk. Though not an exact model, the damped random walk or Ornstein-Uhlenbeck process is an excellent way of approximating the variability seen in AGN. While variability is typically a random noise process, the presence of a binary within the galactic nucleus should cause periodic patterns in the light curves, either either due to accretion of gas onto the individual SMBHs or from gas emission around individual SMBHs being Doppler boosted by their relativistic velocities [1]. Because of the initial random noise in AGN light curves, the identification of periodicity in data becomes complicated. Simply using periodograms to identify periodic changes can lead to false results, given the periodic nature of noise over a short period of time. This summer, I attempted to use the full-width half maximum (FWHM) of peaks in the **Lomb-Scargle Periodogram** (LSP) to differentiate noise from true periodicity.

2 The Lomb-Scargle Periodogram

The LSP is an algorithm that allows for the detection of many kinds of periodic signals, in this case for AGN light curves. The LSP is applied to such signals to estimate the Fourier power as a function of the oscillation frequency, with peaks indicating dominant frequencies in the data [8]. In our case, the highest peak can be used to identify the periodicity of the AGN. Originally, the `Astropy` package was chosen to implement the LSP in Python, given that it is widely used for astronomy. But for early simulations, the Nyquist frequency was invariably detected as a stronger periodicity in the data. LSP is normally used for unevenly sampled periodic signals, making it invaluable for AGN signals but becoming a problem with evenly-sampled simulations. This issue was easily resolved by implementing LSP through `Gatspy`, yielding a single prominent peak at the appropriate period or frequency.

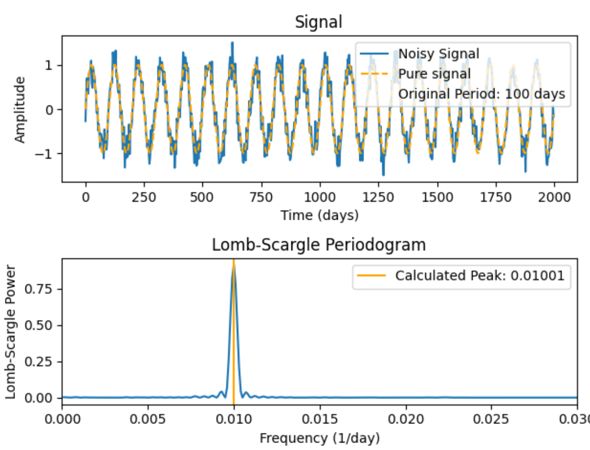

Figure 1: *Above: Simple sine wave with Gaussian noise Below: Lomb-Scargle Periodogram, with strongest peak at the true frequency.*

Fig. 1 shows an analysis of a simple sine wave plotted with Gaussian noise, with obvious periodicity ranging over approximately 400 days. Because the only noise here is Gaussian, the resulting periodogram shows an excellent estimate of the frequency present, with a very narrow peak and very few small secondary peaks.

3 Coherence Time as a Measure of Periodicity

By generating a periodogram of a given signal, it is possible to identify peaks which show the dominant frequencies in the data. Noise artifacts lead to some peaks in the signal, but periodicity which fades within the observation period - as stochastic noise should - will be identifiable by a broader full-width half maximum (FWHM) in the periodogram. This introduces the idea of coherence time as a way to distinguish signals from SMBHBs from noise. The profile of the LSP most closely resembles a Lorentzian, defined by the following equation:

$$L = \frac{A\gamma^2}{(x-x_0)^2+\gamma^2} \tag{1}$$

With this equation, x_0 is the frequency at the peak, while the full-width half maximum (FWHM) is given by 2γ. The quality factor Q associated with this is then $\frac{x_0}{2\gamma}$, and the coherence time τ_c is $\frac{Q}{\pi x_0}$. Implementing this in Python, a curve fitting algorithm is applied, knowing the location of the peak. Amplitude and γ values are varied in order to determine γ for the peak, and therefore the FWHM. In the context of detected periods, it is difficult to determine exactly what information we can derive from the coherence time. Coherence time relates to the foreseeable continuation of a trend, or how long the

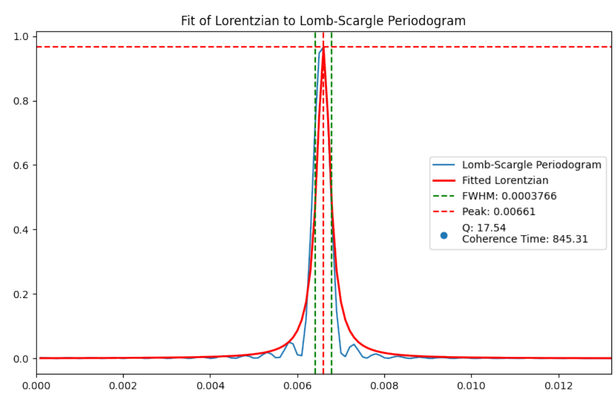

Figure 2: *Lorentz fit to LSP of a randomly generated sinusoidal signal with Gaussian noise and a period of approximately 150 days.*

signal will maintain its periodicity. But this is affected by factors such as the baseline, or the length of the observing time. This is demonstrated by running our LSP and calculation algorithm on sinusoids generated with increasing periods along several different baselines. Fig. 3 shows the increasing trend, with damping factors being higher for longer baselines. This makes sense, as periodicities observed for longer periods of time can more conceivably be predicted to continue.

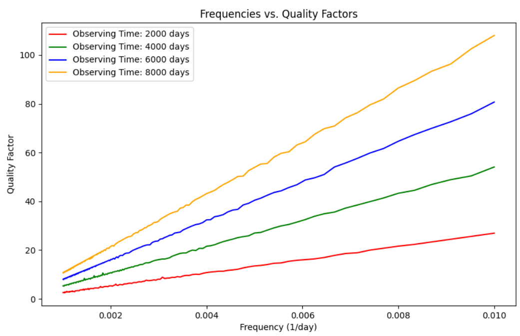

Figure 3: *Plot of quality factors (Q) with respect to periods over several baselines.*

4 Real Data

Data were obtained from the Zwicky Transient Facility (ZTF) on "suspect" sources which may be SMBHBs. Applying the LSP algorithm proved tricky to these data, as many more peaks existed in the real LSP and interfered with curve fitting. Further edits to the code were successfully made to allow for the fitting of a Lorentzian profile to both simulated and real light curves (Fig. 4).

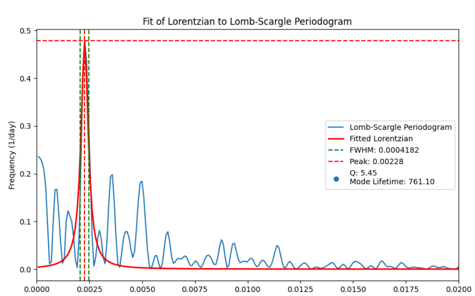

Figure 4: *Periodogram of real light curve, observation period 2500 days.*

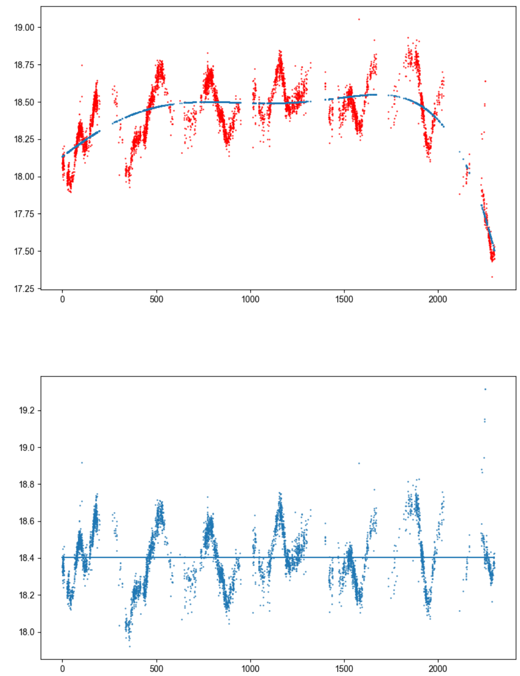

Figure 5: *Fifth-order polynomial detrending algorithm applied to data with an overall trend to flatten and allow better analysis of the periodic pattern.*

Another issue presented by real data is the possibility of detecting longer periods than desired due to overall, slower trends in the data, as well as the inevitable occurrence of outlier points. To fix this issue, a fifth-order polynomial fitting algorithm was written and applied to real light curves to "flatten" them and thus help the periodogram detect the desired frequencies to analyze.

5 Simulating Noise

In earlier discussions of LSP, we added Gaussian noise to the periodic signal. However, AGN noise that poses the largest problem with LSP analysis is best modeled using an Ornstein-Uhlenbeck damped random walk process. This is defined by the following stochastic differential equation:

$$dX(t) = -\tau X(t)\,dt + \sigma dW(t) \tag{2}$$

Where τ is the characteristic timescale of reversion to the mean, σ is the noise amplitude, and $dW(t)$ is a Wiener noise process that introduces the randomness. Because of this random component, the differential equation has a family of solutions. For these simulations, we use a discretized equation, which when run will generate one of the solutions at random.

$$X_i = \theta + (X_{i-1} - \theta)e^{-\frac{\Delta t}{\tau}} + \varepsilon_n \sqrt{\frac{\tau\sigma^2}{2}\left(1 - e^{-\frac{2\Delta t}{\tau}}\right)} \tag{3}$$

This simulated noise is evident in Fig. 6, which is generated using τ = 200 over 2000 days. While the characteristic timescale guides the signal's return to the mean, the process remains random and does not always follow it exactly. In order to compare noise to real or simulated signal, it is necessary then to keep generating signals over the same baseline with a comparable τ to the period calculated from the signal until it provides a fair match to the signal. After detrending, a periodogram can be calculated and coherence time can be obtained in order to compare the two.

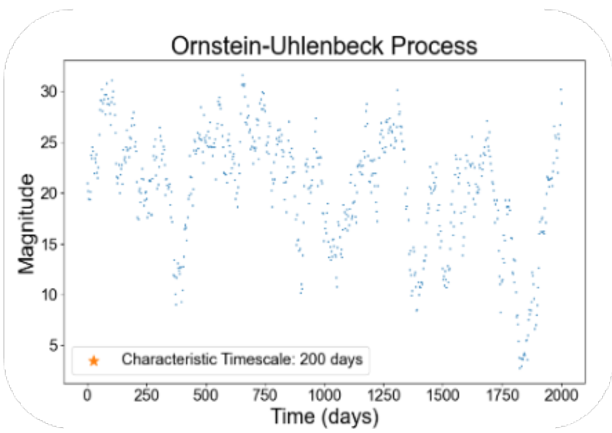

Figure 6: *Correlated noise over observing time of 2000 days.*

6 Conclusion

This summer we developed the tools to calculate periodograms for both real and simulated signals, as well as for random noise processes. We also created a Lorentzian fitting program to calculate Q-factor and coherence time, as well as a program to remove trends in real data that interfere with periodogram calculation. We also programmed tools to simulate random noise processes for comparison with real data, starting with simulated timeseries and applying results to real data from suspect sources. While we have been able to make comparisons between simulated periodicities and simulated noise processes in terms of coherence time, the next step is to write code to automate this better, generating many damped random walk processes and using curve fitting algorithms to select best matches to compare more efficiently to the signal, whether real or simulated. By having more accurate results, it will then be easier to apply to more data from a 20-year period between the Catalina Real-Time Transient Survey (CRTS) and the Zwicky Transient Facility (ZTF). In continuation of this project, we hope to find SMBHBs with periods of less than 100 days and from there to analyze sources of interest, determining ones that are about 10 years from their merger time so that when LISA becomes a reality our results can be verified.

7 Acknowledgements

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8 References

[1] Maria Charisi, Stephen R Taylor, Jessie Runnoe, Tamara Bogdanovic, and Jonathan R Trump. "Multimessenger time-domain signatures of supermassive black hole binaries". In: *Monthly Notices of the Royal Astronomical Society* 510.4 (Dec. 2021), pp. 5929–5944. ISSN: 0035-8711. DOI: 10.1093/mnras/stab3713. eprint: https://academic.oup.com/mnras/article-pdf/510/4/5929/42297198/stab3713.pdf. URL: https://doi.org/10.1093/mnras/stab3713.

[2] B. P. Abbott et al. "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs". In: *Physical Review X* 9.3 (2019), p. 31040. ISSN: 21603308. DOI: 10.1103/PhysRevX.9.031040. arXiv: 1811.12907. URL: https://doi.org/10.1103/PhysRevX.9.031040.

[3] R. Abbott et al. "GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run". In: *Phys. Rev. X* 11 (2 2021), p. 021053. DOI: 10.1103/PhysRevX.11.021053. URL: https://link.aps.org/doi/10.1103/PhysRevX.11.021053.

[4] The LIGO Scientific Collaboration et al. *GWTC-2.1: Deep Extended Catalog of Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run*. 2021. arXiv: 2108.01045 [gr-qc].

[5] The LIGO Scientific Collaboration et al. *GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run*. 2021. arXiv: 2111.03606 [gr-qc].

[6] R. W. Hellings and G. S. Downs. "Upper limits on the isotropic gravitational radiation background from pulsar timing analysis." In: 265 (Feb. 1983), pp. L39–L42. DOI: 10.1086/183954.

[7] Pau Amaro-Seoane et al. "Laser Interferometer Space Antenna". In: *arXiv e-prints*, arXiv:1702.00786 (Feb. 2017), arXiv:1702.00786. DOI: 10.48550/arXiv.1702.00786. arXiv: 1702.00786 [astro-ph.IM].

[8] Jacob T. VanderPlas. "Understanding the Lomb–Scargle Periodogram". In: *The Astrophysical Journal Supplement Series* 236 (May 2018). DOI: 10.3847/1538-4365.