Proceedings of the 4th International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/108/2025.23282

A Search for A Planet Near A Black Hole

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Abstract: Gaia BH1 is the first black hole discovered using the data from Gaia, which is orbited by a sun-like companion star and has plenty of RV data. Motivated by the enthusiasm to find exoplanets and the high precision of the data about Gaia BH1 from the spectrograph "ESPRESSO", after finding the best-fit model of the star's orbit, I searched the RV residuals for periodic signals, estimated the intensity of the signal, tested the statistical significance and calculated the parameters for the planet candidate. Finally, we can conclude that the signal, which has a 15.2-day period and $4m/s$ amplitude could not have been produced by random noise. However, the planet candidate is not stable, and it may encounter the black hole or escape in at least about 20 years based on different mean anomalies. It is possibly due to the assumptions we made to avoid overfitting because it is close to the edge of being stable. Now we only have 40 data covering a single period, and we hope to get 100 more data from further observation because it may lead to details to replace the assumptions. Therefore, it would be possible for us to verify whether it is an exoplanet.

Keywords: exoplanets, strange phenomena, transits and occultations

1. Introduction

In the essay [1], Gaia BH1 was discovered through astrometric technique and RV follow-up. They noticed the elliptical motion of some stars, and they examined the candidates using RV method, which involves analyzing the Doppler shift in the star's spectral absorption lines. Finally, they confirmed the existence of Gaia BH1 given the high lower mass limit and stringent limits on the light contributions of a luminous companion. Driven by the desire to explore space, this essay examines whether it is possible for a planet to exist around the star. The analysis was conducted because there had not been a convincing discovery of a planet around a black hole. In the essay [2], a controversial candidate was found near a source of X-ray, but only one transit was observed and analyzed in that essay and the exact type of the celestial body emitting X-ray was unclear, which means it can be a neutron star or a black hole. Therefore, we did not regard that candidate as a planet. However, finding a planet near the black hole is not completely impossible. In the essay [3], two planets near a pulsar were found, which indicates that planets can possibly survive through supernova, because the pulsar could only form after a supernova. Therefore, it is possible for planets near black holes to survive through the supernova, which is hypothesized to be launched during the formation of some black holes, although the formation process for Gaia BH1 is not clear yet.

We chose this black hole because it was one of the few dormant black holes with high-precision RV data while lots of other known black holes were discovered through the X-ray method, which analyzes the X-ray data from the companion star. However, those stars are not suitable for exoplanet search, because they are highly distorted, often rapidly rotating and very faint due to the great distance. Besides, given that the data from other instruments, including HIRES, FEROS, MagE, etc., have high errors, this essay only examined the data from ”ESPRESSO”, which created the data with the least uncertainty among the available ones.

Finally, we hope our possible discovery can enable further discussions on the formation of black holes, because planets surviving through the process had not been found yet. If a planet is found, it can possibly promote new theories of the formation of black holes.

The following part of this essay will cover the detailed process of the analysis and briefly discuss the results.

2. Methods and results

All data we use in this essay is from [1]. Only the high-precision data from ESPRESSO, which have errors around few m/s, were analyzed and other data, which have errors from about 10 to over 1000 m/s, were filtered out. This allows us to notice small motion of the star, gives us the potential to search for exoplanets with smaller masses, because the same objects might be ignored using data from all the instruments due to a lower signal-to-noise ratio.

2.1. Spectroscopic orbit of the star around the black hole

We first assumed the star and the black hole were in a binary without any great impacts from other celestial bodies. We adopted the equations from [4], for simulating the relationship between the black hole and the star. The best-fit parameters describing the orbit of the binary system were obtained through a least-square minimization fit, during which all the values can be varied:

$$V_r = K[\cos(\nu + \omega_*) + e\cos\omega_*] + \gamma. \tag{1}$$

in which ν can be calculated through the equations:

$$\tan\frac{\nu}{2} = \sqrt{\frac{1+e}{1-e}}\tan\frac{E}{2} \tag{2}$$

and:

$$M = \frac{2\pi(t - T_0)}{P} = E - E\sin E \tag{3}$$

In the listed equations, ν, M and E are the true anomaly, mean anomaly and eccentric anomaly of the binary, respectively.

Table 1 shows the best-fit values of the parameters and 1σ uncertainty. Comparing to the parameters in [1] calculated through both astrometry and RV, our data, our fit has a slightly larger argument of periastron and center-of-mass velocity, while other parameters are close to theirs. The deviation in Figure 1 is going to be analyzed for the search of a planet.

2.2. Period search of the residuals

In order to find a periodic pattern inside the deviations between the raw RV data and the predicted RV from the model, we created the Lomb-Scargle periodogram according to [5] and analyzed the

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Table 1: Parameter values.

Parameter	Symbol	Value
Center-of-mass RV	γ [km/s]	48.3824 ± 0.0029
Period	P [days]	185.368 ± 0.014
Semi-amplitude	K [km/s]	65.3767 ± 0.0017
Eccentricity	e	0.432238 ± 0.000047
Argument of periastron	ω_* [deg]	0.288152 ± 0.000072
Periastron time	T_0 [HJD-2457389.0]	2.35 ± 0.21

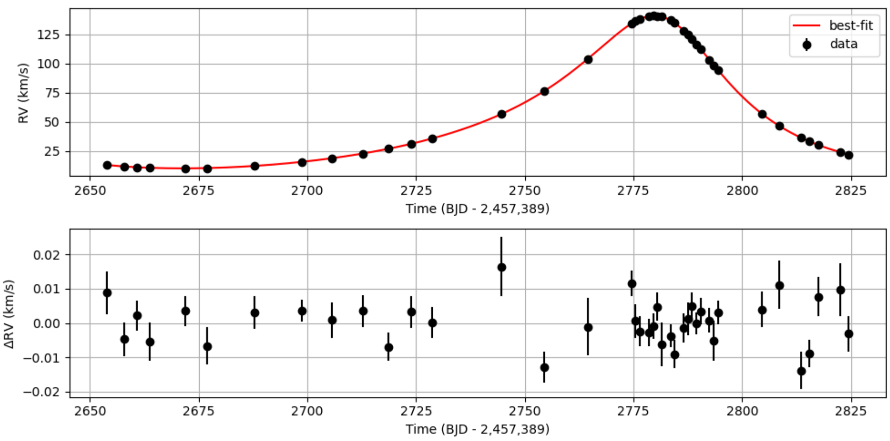

Figure 1: Top panel: Gaia BH1 ESPRESSO data. RV versus time. Overplot best-fit model. Bottom panel: Deviations between data and best-fit model.

peak in the figure. The height of the peak indicates the strength of the potential periodic pattern. The equations used for the figure were:

$$P_{\rm LS}(f) = \frac{1}{2}\left\{\frac{\left(\sum_n g_n \cos(2\pi f[t_i-\tau])\right)^2}{\sum_n \cos^2(2\pi f[t_i-\tau])}\right\} + \left\{\frac{\left(\sum_n g_n \sin(2\pi f[t_i-\tau])\right)^2}{\sum_n \sin^2(2\pi f[t_i-\tau])}\right\} \tag{4}$$

in which τ can be calculated through the equation:

$$\tau = \frac{1}{4\pi f}\tan^{-1}\left(\frac{\sum_n sin(4\pi f t_n)}{\sum_n cos(4\pi f t_n)}\right) \tag{5}$$

The g and t refer to each element of RV data and the timestamp of each velocity datum. For each frequency f, we can obtain a P_{LS}, and we can create the periodogram by plotting the P_{LS} versus f.

We created the periodogram covering periods from 1 to 30 days because the time span of our data was only 175 days and our data were not densely distributed. If the period is too large, the data would not fully cover any of the periods while over-fitting problems may occur when the period can be too small. Figure 2 shows the periodogram in which we can observe an obvious peak at the period of 15.2 days. This implies that there might be a periodic pattern in the deviations of the star's RV data.

2.3. Spectroscopic orbit of the planet candidate

We then assume the deviations were the impact from other celestial bodies, potentially an exoplanet around the star. Using the same least-square minimization through which Figure 1 was created, we

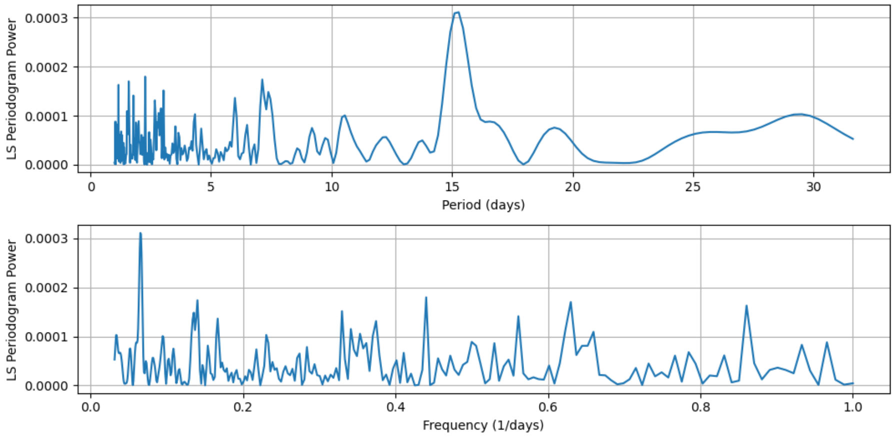

Figure 2: Top panel: LS power versus the period of the planet motion. Bottom panel: LS power versus the frequency of the planet motion.

obtained the best-fit parameter for the unknown celestial body. To be specific, since the number of data was only 40, we set the eccentricity of the orbit and the longitude of periastron to both be 0 for convenience and to avoid over-fitting. However, the chi-square value is slightly higher than in an ideal situation: It reached 43.5 while the degree of freedom is just 36. The possibility for this to be caused by random independent Gaussian noise is 18%, which is statistically acceptable.

Figure 3 shows the data with the best-fit model. The data covered a whole period at around $t - 2457389 = 2775$ in the upper panel. The bottom panel shows the deviations that were still not explained by the impact of the planet. Besides, Figure 4 shows the RV deviations after folding them into a single period. The periodic pattern can be illustrated more clearly compared to the previous figure containing multiple periods.

Table 2: Parameter values.

Parameter	Symbol	Value
Center-of-mass RV	γ [km/s]	-0.00065 ± 0.00080
Period	P [days]	15.19 ± 0.18
Semi-amplitude	K [km/s]	0.0047 ± 0.0011
Periastron time	T_0 [HJD-2457389.0]	2654.03 ± 1.41

2.4. Test of statistical significance

To distinguish the periodic pattern with some coincidences from random noise, we applied a Monte-Carlo test to validate its statistical significance. We created simulated RV data. The noises were set to have zero mean, while the timestamps were the same as the raw data, and the standard deviation was set equal to the error of raw RV data on the same timestamp. We performed 10000 times of simulation and found that the possibility for the random noise to have a peak in periodogram higher than the one of the raw data is only 0.11%. Therefore, although the reason for this periodic pattern was still unclear, it was unlikely to be caused purely by some random noises. Possibly it was caused by some star activities or rare events, but it could also be caused by an exoplanet.

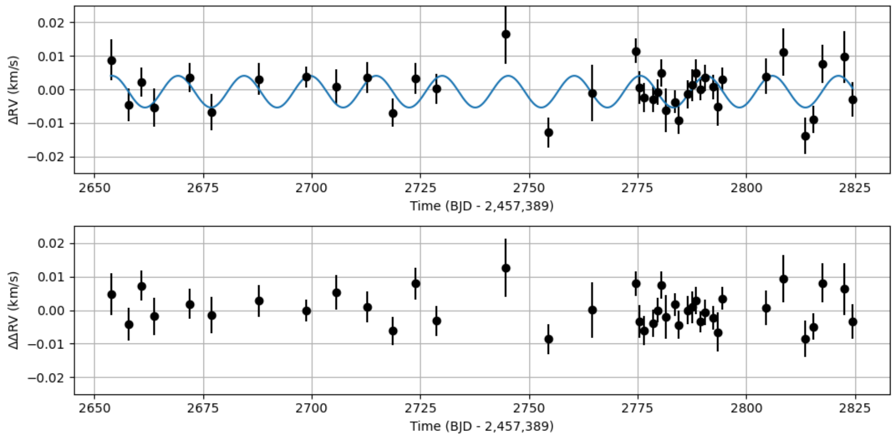

Figure 3: Top panel: RV deviation versus BJD-2457389 days with the best fit model, Bottom panel: deviations between RV and the best fit model of planet's impact.

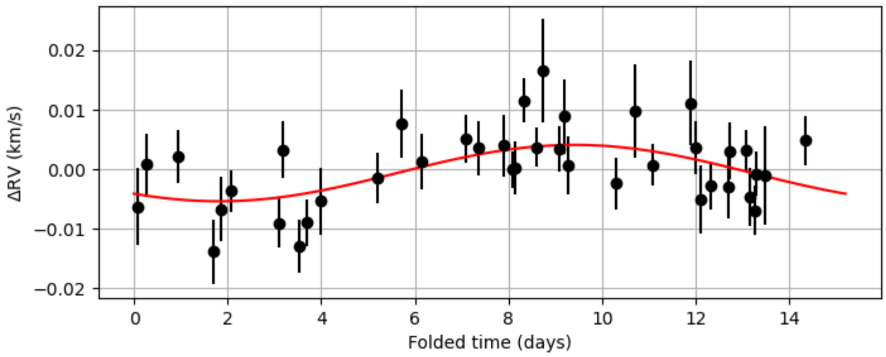

Figure 4: RV deviations versus the folded time.

In Figure 5, it shows the distribution of the simulative peak and the red line represents the peak value of the raw data. The red line is on the right of most of the simulative peaks, while the number of peaks on its right indicates the possibility for the periodic pattern to be caused purely by some random noises. Assuming that the planet candidate exists, additionally, we calculated the minimum mass of the planet, the semi-major axis of its orbit, and examined whether it is stable. This involves Kepler's third law, which is a generalized law allowing us to derive the semi-major axis from the central mass and period:

$$a_{planet} = \sqrt[3]{M_* T^2} \tag{6}$$

in which M_* is expressed in solar mass and T is expressed in year. The semi-major axis is 0.117 au, according to the mass of the star given by [1] and the best fit period. Moreover, the minimum mass of the planet can be calculated through

$$M_{planet} \sin I = \frac{KPM_*}{2\pi a_{planet}} \tag{7}$$

Consequently, the minimum mass is 17.46 $M_\oplus$, which seems plausible for a planet because it is close to the mass of Neptune. The inclination I is unknown, so the actual mass of the planet can not

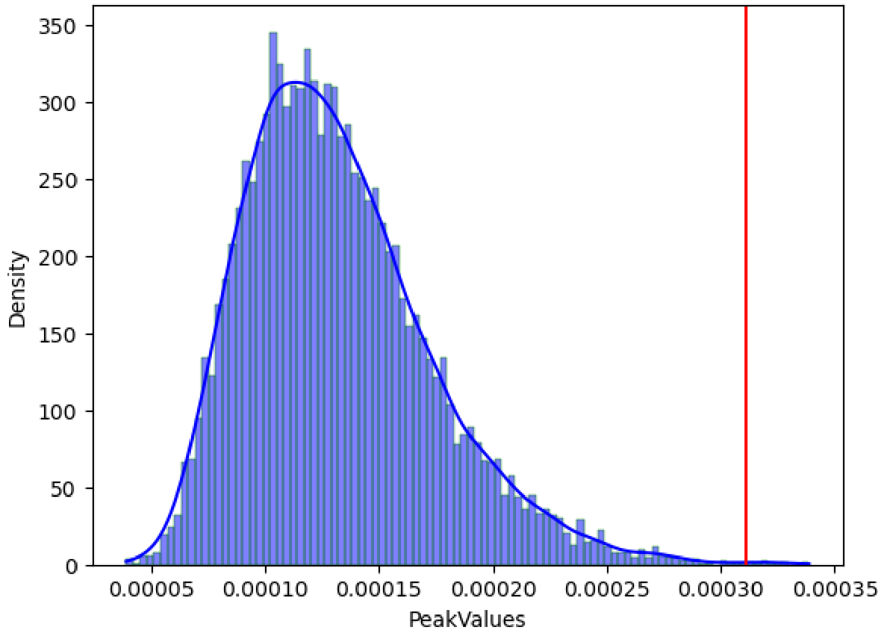

Figure 5: The density of occurrence versus the peak height of the Lomb-Scargle periodogram of each set of random noise.

be calculated. Besides, the relationship between the long-term stability and the semi-major axis had been examined in [6]. According to the equation:

$$\begin{aligned}\frac{a_c}{a_b} = (0.464 \pm 0.006) - (0.380 \pm 0.010)\mu - \\ (0.631 \pm 0.034)e + (0.586 \pm 0.061)\mu e + \\ (0.150 \pm 0.041)e^2 - (0.198 \pm 0.074)\mu e^2\end{aligned} \tag{8}$$

The μ stands for $\frac{M_2}{M_1+M_2}$, in which M_2 is the mass of Gaia BH1 and M_1 is the mass of the star. The a_c is the critical semi-major axis, and planets are considered to be dynamically stable if their semi-major axis is smaller than the critical value. The a_b stands for the binary semi-major axis, which is the semi-major axis of the star and Gaia BH1. Adopting the data from [1] and our prior fit, the critical semi-major axis is 0.07 in the unit of the binary semi-major axis. However, the actual semi-major axis of the planet candidate is 0.0837 times the semi major axis of the binary orbit which is slightly larger than the critical value. Therefore, the planet might not be dynamically stable.

Since the semi-major axis of the planet candidate is close to the crucial semi-major axis, and the actual mass ratio is slightly out of the range discussed in [6], we decided to run a simulation on our own assuming the planet is on the orbital plane involving the star and the black hole. We checked the encounters and escapes of the planet candidate. An encounter is defined as the circumstance under which the distance between the black hole and the planet is less than 0.25 of the semi-major axis of the star, and an escape is defined as when the planet candidate is more than 15 au. As a result, encounters and escapes occur in about 20000 years if the mean anomaly is 0 or 180 degrees, but can also occur in less than 100 years if the mean anomaly is different. Therefore, by the standard of astronomy, the planet candidate is not stable.

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3. Conclusion

This tree essay raises the possibility of the existence of an exoplanet orbiting the star near Gaia BH1. However, the data only covered a single period, which means the signal might have been caused by some events instead of an exoplanet. In order to further verify the existence of the planet candidate, more than 100 data covering at least 5 periods from high-precision instruments like ESPRESSO and Keck Planet Finder will be valuable. Possibly, we can get more details about the orbit of the planet and the star, including the inclination, mean anomaly we should adopt, etc., to replace our current assumptions. Therefore, the result of the stability test may vary and the discovery of the planet might promote the development of theories about the black holes' formation processes.

References

[1] El-Badry K, Rix HW, Quataert E, Howard AW, Isaacson H, Fuller J, et al. A sun-like star orbiting a black hole. Monthly Notices of the Royal Astronomical Society. 2023;518(1):1057-85.
[2] Di Stefano R, Berndtsson J, Urquhart R, Soria R, Kashyap VL, Carmichael TW, et al. A possible planet candidate in an external galaxy detected through X-ray transit. Nature Astronomy. 2021;5(12):1297-307.
[3] Wolszczan A, Frail DA. A planetary system around the millisecond pulsar PSR1257+ 12. Nature. 1992;355(6356):145-7.
[4] Wright JT, Gaudi BS. Exoplanet detection methods. arXiv preprint arXiv:12102471. 2012.
[5] VanderPlas JT. Understanding the lomb–scargle periodogram. The Astrophysical Journal Supplement Series. 2018;236(1):16.
[6] Holman MJ, Wiegert PA. Long-term stability of planets in binary systems. The Astronomical Journal. 1999;117(1):621.