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Verifying Stellar Black Hole Candidates Using Radial Velocity Method

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Abstract:
This study gives a quick introduction to stellar black holes, explores the drawbacks of identifying the unseen companion only by analysing the X-ray emission from X-ray binaries, derives the radial velocity method, and tests it using two black hole candidates. The dark companion in A0620-00 has a radial velocity semi-amplitude of $459.6 \pm 13.91\,\mathrm{km\,s^{-1}}$ M⊙, and its computed mass is 3.18 ± 0.16 M⊙, above the 3 M⊙ Tolman–Oppenheimer–Volkoff limit on neutron star mass. With the two recorded X-ray outbursts, its identity as a black hole is largely verified. On the other hand, the dark companion in LMC X-3 has a radial velocity semi-amplitude of $219.3 \pm 10.47\, km\, s^{-1}$ and a computed mass of 6.98 ± 0.56 M⊙, exceeding the upper mass limit of neutron star. Its powerful and very fluctuating X-ray emission is supported by observations, and thus helps to basically corroborate that it is indeed a black hole. In the search for black holes, the two methods presented to ascertain the nature of the dark companion are both essential and needed. After classifying the partners and adding them to the list of potential black hole candidates using X-ray emission analysis, the mass of the companion can be confirmed by calculating the star's radial velocity. Nonetheless, identification errors are not uncommon; the computed mass varies within an unavoidable range, giving rise to disparate findings. Future research may compare the differences between black hole binaries and neutron star binaries and look for evidence to increase the veracity and trustworthiness of the results.

Keywords: Radial Velocity Method, Black Hole Binaries, X-Ray Emission Analysis.

1. Introduction

Being the end state of massive stars, potential candidates of supermassive black holes, and origins of energetic phenomena in the universe, stellar black holes have always been a major topic of investigation in astrophysics [1]. The detection of stellar Black Holes (BHs) in binary star systems, which are predomi-

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nantly identified through X-ray emission from the gas of a companion star accreting onto the BHs, contributes crucially to verifying current models of stellar evolution [2, 3]. Nevertheless, star-black-hole binaries do not always accrete gas and possess X-ray-emitting systems, the companion could instead be a neutron star [4, 5]. Under such cases, the dynamical mass of the dark companion is estimated by observing the motion of the companion star and can be confirmed to be a black hole if the mass is greater than approximately 3 solar masses (M☉) [6]. Similar to how exoplanets are detected by the radial velocity method (as planets tug their host stars and induce slight periodic movements), significant radial velocity shifts could be utilized to infer the existence of invisible companions [7, 8].

This research attempts to explore potential candidates of stellar BHs detected by X-ray emissions, and verify their identities through analyzing radial velocity variations in optical spectra. Finally, the accuracy of the radial velocity method will be evaluated.

2. Overview of Stellar Black Holes

As the general theory of relativity predicts, when stars with stellar core (where thermonuclear burning takes place) of mass exceeding 3 M☉ exhaust their nuclear fuel, they could undergo gravitational collapse and give birth to black holes [9]. In cases where the stellar cores have less than 3 M☉, neutron stars or white dwarfs will be their end of evolution instead [10]. Once a black hole is formed, it grows by either amalgamating with other BHs, or by the process of accretion - the consuming of matter. For stellar black holes in binary star systems, the mass supply for accretion is materials and gas from their companion stars. When these matter possess adequate angular momentum that they are not able to fall into the accretor's rotation axis, accretion disks are formed [11]. As matter falls toward the accretor, its velocities get accelerated by the gravitational field of BHs, approaching the speed of light near the event horizon. The atoms mutually rub when disorderly falling towards the event horizon, the vigorous internal friction produced can heat them to temperatures of > 100 million Kelvin, emitting x-ray radiations [2]. Such binary star systems constituted by a regular star and a collapsed one are referred to as X-ray binaries.

3. Stellar BH Candidates

Since it is nearly impossible to observe BHs directly, the x-ray radiation emitted as matter falls into BHs are crucial signals indicating their existence. Nevertheless, it cannot be irrefutably deduced that the invisible companion in X-ray binaries is a BH solely based on this feature since a neutron star can display X-ray emissions with many similar characteristics. For instance, the bimodal behavior, flickering state transitions of accretion disk, had been found appearing in neutron star systems, and hence cannot be used as unparalleled indicators of black holes. When the truly conclusive signatures in the X-ray spectrum, X-ray variability, level of X-ray luminosity, and presence of event horizon are not acquired, the most credible method to eliminate the possibility of the companion being a neutron star is by estimating its dynamical mass and verifying it exceeds the upper mass limit of neutron stars [12]. The upper mass limit of a neutron star, Tolman–Oppenheimer–Volkoff limit, is calculated to be 2.2M☉ - 2.9M☉ in 1996[13]. Accounting for all discrepancies in other research, it is generally accepted that the companion star is a black hole if its mass is greater than 3M☉. This paper will now list two black hole candidates discovered by X-ray emissions, and perform a dynamical mass estimate to verify if they are black holes.

3.1 X-ray binary A0620-00 in quiescence

A0620-00 is a binary star system located in the constellation of Monoceros. It has undergone two X-ray outbursts, making it a strong candidate for stellar black holes [14].

3.2 LMC X-3

LMC X-3 is a binary system located in the Large Magellanic Cloud (a small companion galaxy to the Milky Way), discovered in 1971 by orbiting X-ray telescopes [15]. LMC X-3 emits strong and highly variable X-rays, and large variations have been reported.

4. Determining the Dynamical Mass of Stellar BH Candidates

The amplitude in the sine function, which is the radial velocity, can be determined by fitting a sine graph onto the two candidates' spectroscopic phase of period and radial velocities. With already known parameters of Ma orbital period, and angle of inclination sin(i), the mass of the companion could be obtained using the radial velocity equation.

4.1 Radial Velocity Equation Derivation

Consider a binary star system. Newton's Second Law of motion states for the observed star, with mass M_a states, acceleration a_a, and force F:

$$M_a a_a = F M_a a_a = F \quad (1)$$

For companion star with mass M_b, acceleration a_b, and force F:

$$M_b a_b = F M_b a_b = F \tag{2}$$

Newton's law of gravitation states, with G being the gravitational constant $6.67\times10^{-11} Nm^2kg^{-2}$, s being the distance between centre of two masses:

$$F = \frac{GM_a M_b}{s^2} \tag{3}$$

Substitute equation (1) into (3) gives:

$$M_a r_a = \frac{GM_a M_b}{s^2} \tag{4}$$

$$a_a = \frac{GM_b}{s^2} \tag{5}$$

Substitute equation (2) into (4) gives:

$$M_b r_b = \frac{GM_a M_b}{s^2} \tag{6}$$

$$a_b = \frac{GM_a}{s^2} \tag{7}$$

Equation for circular motion, with velocity v and orbital radius r:

$$a = \frac{v^2}{r} \tag{8}$$

$$a_a = \frac{v_a^2}{r_a} \tag{9}$$

$$a_b = \frac{v_b^2}{r_b} \tag{10}$$

Equate equation (5) and (9):

$$\frac{GM_b}{s^2} = \frac{v_a^2}{r_a} \tag{11}$$

$$v_a^2 = \frac{GM_b r_a}{s^2} \tag{12}$$

Equate equation (7) and (10):

$$\frac{GM_a}{s^2} = \frac{v_b^2}{r_b} \tag{13}$$

$$v_b^2 = \frac{GM_a r_b}{s^2} \tag{14}$$

Center of mass between two stars:

$$M_a r_{a=} M_b r_b \tag{15}$$

$$r_a = \frac{M_b}{M_a} r_b \tag{16}$$

Substitute equation (16) into (12):

$$v_a^2 = \frac{GM_b^2 r_b}{M_a s^2} \tag{17}$$

Star B is much more massive than stat a, $M_a \ll M_b$, $r_a \ll r_b$, $s = r_a + r_b \approx r_b$. Replace r_b by s in equation (17):

$$v_a^2 = \frac{GM_b^2 s}{M_a s^2} \tag{18}$$

$$v_a^2 = \frac{GM_b^2}{M_a s} \tag{19}$$

Replace r_b by s in equation (14):

$$v_b^2 = \frac{GM_a r_b}{s^2} \approx \frac{GM_a s}{s^2} = \frac{GM_a}{s} \tag{20}$$

Now express v_b in terms of the orbital period T:

$$v_b = \frac{2\pi r_b}{T} \approx \frac{2\pi s}{T} \tag{21}$$

$$v_b^2 = \frac{4\pi^2 s^2}{T^2} \tag{22}$$

Equate equation (20) and (22):

$$v_b^2 = \frac{GM_a}{s} = \frac{4\pi^2 s^2}{T^2} \tag{23}$$

$$GM_a = \frac{4\pi^2 s^3}{T^2} \tag{24}$$

$$s = \left(\frac{GM_a T^2}{4\pi^2}\right)^{\frac{1}{3}} \tag{25}$$

Substitute equation (25) into (19):

$$v_b^2 = \frac{GM_b^2}{M_a} \times \frac{1}{s} = \frac{GM_b^2}{M_a} \times \left(\frac{4\pi^2}{GM_a T^2}\right)^{\frac{1}{3}} \tag{26}$$

Further simplify:

$$v_b^2 = \left(\frac{2\pi G}{T}\right)^{\frac{2}{3}} \times \frac{M_b^2}{M_a^{\frac{4}{3}}} = \left(\frac{2\pi G}{T}\right)^{\frac{1}{3}} \times \frac{M_b}{M_a^{\frac{2}{3}}} \tag{27}$$

$$v_a = \left(\frac{2\pi G}{T}\right)^{\frac{1}{3}} \times \frac{M_b}{M^{\frac{2}{3}}} \tag{28}$$

The Doppler shift equation states, with $\Delta\lambda$ being the wavelength shift, λ being the wavelength of source when not moving, c being the speed of light, v_r being the radial velocity:

$$\frac{\Delta\lambda}{\lambda} = \frac{-v_r}{c} \tag{29}$$

Accounting for the angle of inclination between the orbital plane and line of sight $\sin(i)$:

$$|v_r| = -\left(\Delta\frac{2\pi G}{T}\right)^{\frac{1}{3}} \times \frac{M_b \sin(i)}{M_a^{\frac{2}{3}}} \sin(wt) \tag{30}$$

Rearrange to make M_b the subject:

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$$M_b = \frac{v_r M_a^{\frac{2}{3}} T^{\frac{1}{3}}}{(2\pi G)^{\frac{1}{3}}} \quad (31)$$

4.2 Performing Calculations

Table 1 shows the radial velocities of A0620-00 at various spectroscopic phases, with measurements ranging from -383 km/s to 477 km/s and associated uncertainties. Fig.1 illustrates the fitting of a sine curve to the radial velocity data from Table 1, yielding a velocity semi-amplitude of 459.6 ± 13.91 km/s.

Table 1. Spectroscopic phrase and radial velocities of A0620-00

Spectroscopic Phrase	Radial Velocities (kms-1)
0.586	-383±16
0.694	-123±12
0.733	-42±12
0.795	138±8
0.834	238±8
0.888	358±8
0.926	428±8
0.981	477±7
1.019	466±7
1.073	419±8

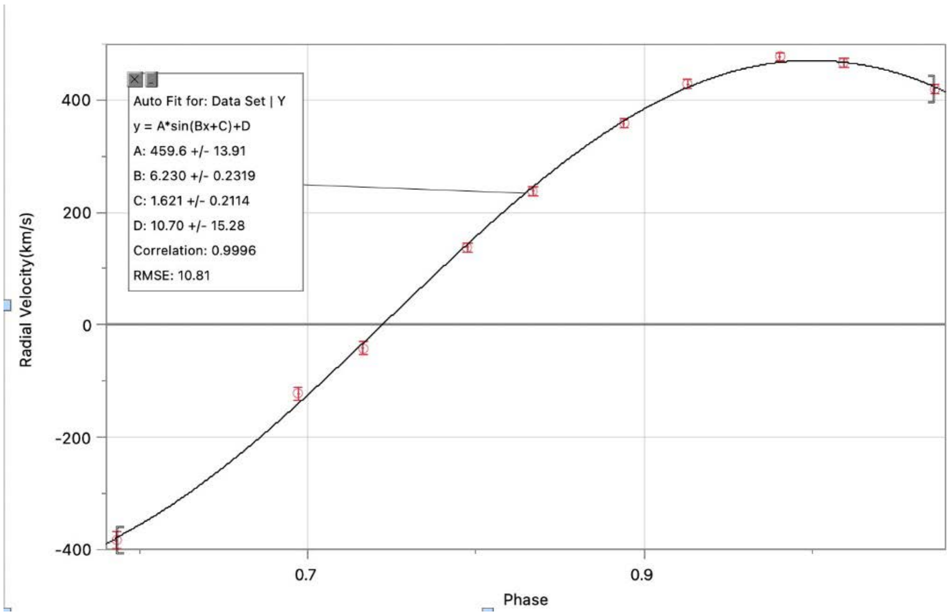

Fig. 1 Fitting a sine curve for radial velocities data in Table 1, the velocity semi amplitude is 459.6 ± 13.91 **km s-1.**

4.3 LMC X-3

Table 2 provides radial velocity measurements of LMC X-3 at various spectroscopic phases, ranging from 41 km/s to 522 km/s, while Fig. 2 shows the sine curve fit to this data, resulting in a velocity semi-amplitude of 219.3 ± 10.47 km/s.

Table 2. Spectroscopic phrase and radial velocities of LMC X-3

Spectroscopic Phrase	Radial Velocities (kms-1)
0.47	85±21
0.23	365±22
0.39	149±18
0.11	424±52
0.16	472±46
0.23	376±21
0.77	362±18
0.82	387±23
0.38	128±25
0.48	41±14
0.55	74±11
0.03	518±11
0.10	522±24
0.15	455±6
0.63	130±17
0.68	250±15
0.75	321±13

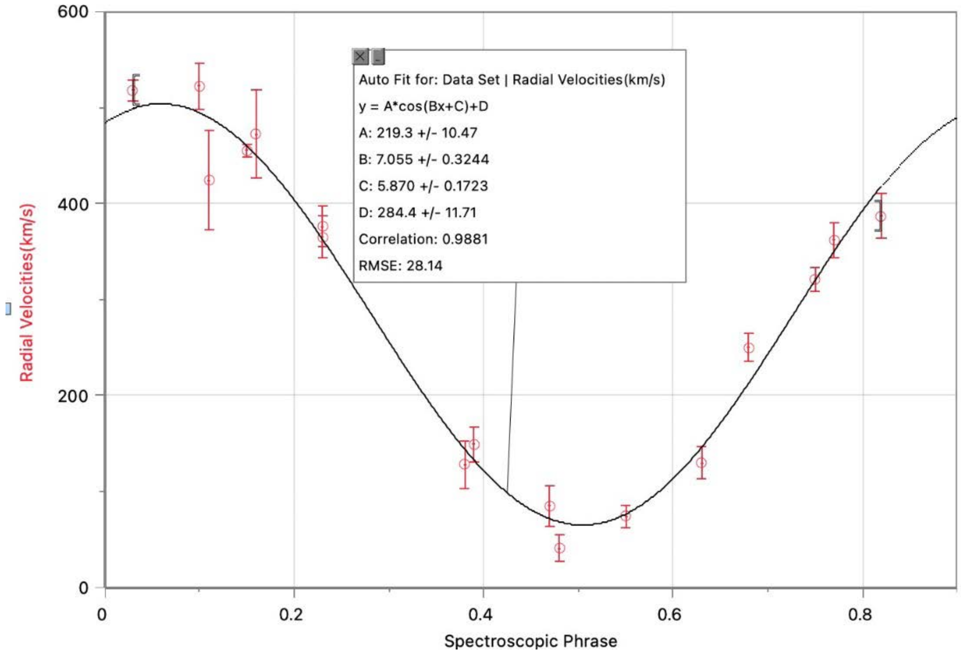

Fig. 2 Fitting a sine curve for radial velocities data in Table 2, the velocity semi amplitude is $219.3 \pm 10.47\ km\ s^{-1}$.

5. Conclusion

To conclude, this research presents a brief overview of stellar black holes, discusses the limitation of solely relying on X-ray emission from X-ray binaries to determine the unseen companion's identity, provides a derivation of the radial velocity method, and tests it on two black hole candidates. The radial velocity semi-amplitude of the dark

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companion in A0620-00 reveals to be $459.6 \pm 13.91\, km\, s^{-1}$, and have a calculated mass of 3.18 ± 0.16 M ⊙ , exceeding the Tolman–Oppenheimer–Volkoff limit of mass of neutron star at 3 M ⊙ . Accompanied by the two X-ray outbursts detected, it is mostly confirmed to be a black hole. The radial velocity semi-amplitude of the dark companion in LMC X-3, on the other hand, is revealed to be $219.3 \pm 10.47\, km\, s^{-1}$ M ⊙ , with a calculated mass of 6.98 ± 0.56 M ⊙ , exceeding the Tolman–Oppenheimer–Volkoff limit of mass of neutron star. Accompanied by the observation of its strong and highly variable X-ray emission, it is mostly confirmed to be a black hole as well. The two approaches introduced to determine the dark companion's nature are both crucial and indispensable in the searching of black holes. X-ray emission analysis categorizes the companions and places some in the black hole candidate list, the radial velocity of the star may then be obtained to calculate its companion's mass for final confirmation. However, errors in identifications are not rare, the calculated mass fluctuates in an unignorable range that leads to different conclusions. To enhance the credibility and certainty of results, future research may conduct comparative studies on the distinction between black hole binaries and neutron star binaries, and seek evidence in the accretion disk in black holes for further confirmation.

References

[1] Mirabel F. The formation of stellar black holes. New Astronomy Reviews, 2017, 78: 1–15.

[2] Evidence for Black Holes. Physics LibreTexts, 2016.

[3] Remillard R A, McClintock J E. X-Ray Properties of Black-Hole Binaries. Annual Review of Astronomy and Astrophysics, 2006, 44(1): 49–92.

[4] Dunn H, Fender R P, Körding E G, Belloni T, Cabanac C. A global spectral study of black hole X-ray binaries. Monthly Notices of the Royal Astronomical Society, 2010, 403(1): 61–82.

[5] Liu J, Zhang H, Howard A W, et al. A wide star–black-hole binary system from radial-velocity measurements. Nature, 2019, 575: 618–621.

[6] Clavel M, Dubus G, Casares J, Babusiaux C. Using radial velocities to reveal black holes in binaries: A test case. Astronomy and Astrophysics, 2021, 645: A72–A72.

[7] Color-Shifting Stars: The Radial-Velocity Method. The Planetary Society, 2020.

[8] Gibbons G W, Hawking S W. Evidence for Black Holes in Binary Star Systems. Nature, 1971, 232(5311): 465–466.

[9] Frolov V P, Novikov I D. Black Hole Physics. SpringerLink, 2023.

[10] Frank J. Accretion disk. Encyclopedia Britannica, 2024.

[11] Ziółkowski J. Black Hole Candidates. ArXiv, 2003.

[12] Kalogera V, Baym G. The Maximum Mass of a Neutron Star. The Astrophysical Journal, 1996, 470(1): L61–L64.

[13] McClintock J E, Remillard R A. The black hole binary A0620-00. The Astrophysical Journal, 1986, 308: 110.

[14] LMC X-3 Fact Sheet. StarDate's Black Hole Encyclopedia, 2024.

[15] Cowley A P, Crampton D, Hutchings J B, Remillard R, Penfold J E. Discovery of a massive unseen star in LMC X-3. The Astrophysical Journal, 1983, 272: 118.