# Search for a Black Hole Binary in Gaia DR3 Astrometric Binary Stars with Spectroscopic Data 

 Daichi Tsuna ${ }^{7}$ (1)<br>${ }^{1}$ Department of Earth Science and Astronomy, College of Arts and Sciences, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo, 153-8902, Japan tanikawa@ea.c.u-tokyo.ac.jp<br>${ }^{2}$ National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan<br>${ }^{3}$ Institute of Statistical Mathematics, 10-3 Midoricho, Tachikawa, Tokyo, 190-8562, Japan<br>${ }^{4}$ Center for Gravitational Physics and Quantum Information, Yukawa Institute for Theoretical Physics, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto, 606-8502, Japan<br>${ }^{5}$ Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, 255-8582, Japan<br>${ }^{6}$ Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, 113-0033, Japan<br>${ }^{7}$ Research Center for the Early Universe (RESCEU), School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan<br>${ }^{8}$ Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC, V6T 1Z1, Canada<br>Received 2022 September 20; revised 2023 February 23; accepted 2023 February 24; published 2023 April 3


#### Abstract

We report the discovery of a candidate binary system consisting of a black hole ( BH ) and a red giant branch star in Gaia DR3. This binary system was discovered from 64,108 binary solutions for which both astrometric and spectroscopic data are available. For this system, the astrometric and spectroscopic solutions are consistent with each other, making this system a confident candidate of a BH binary. The primary (visible) star in this system, Gaia DR3 5870569352746779008, is a red giant branch star whose mass is quite uncertain. Fortunately, despite the uncertainty of the primary's mass, we can estimate the mass of the secondary (dark) object in this system to be $>5.68 M_{\odot}$ with a probability of $99 \%$, based on the orbital parameters. The mass of the secondary object is much larger than the maximum neutron star mass $\left(\sim 2.0 M_{\odot}\right)$, which indicates that the secondary object is likely a BH. We argue that, if this dark object is not a BH , this system must be a more exotic system, in which the primary red giant branch star orbits around a quadruple star system (or a higher-order multiple-star system) whose total mass is more than $5.68 M_{\odot}$. If this is a genuine BH binary, this has the longest period ( $1352.22 \pm 45.81$ days) among those discovered so far. As our conclusion entirely relies on Gaia DR3 data, independent confirmation with follow-up observations (e.g., long-term time-series spectra) is desired.


Unified Astronomy Thesaurus concepts: Astrometric binary stars (79); Spectroscopic binary stars (1557); Stellar mass black holes (1611)

## 1. Introduction

Stellar-mass black holes (BHs) are the final state of massive stars with several $10 M_{\odot}$ (e.g., Woosley et al. 2002). BHs are not always dark, especially when they are members of close binary stars. Thus, they have been discovered as X-ray binaries (e.g., Casares et al. 2017) and gravitational-wave transients (Abbott et al. 2019, 2021; The LIGO Scientific Collaboration et al. 2021). Nevertheless, since such BH populations are rare, just a handful of BHs are known. So far, $\sim 100 \mathrm{BHs}$ have been detected as X-ray binaries in the Milky Way (Corral-Santana et al. 2016), while there should be $\sim 10^{8} \mathrm{BHs}$ in the Milky Way (e.g., Shapiro \& Teukolsky 1983; van den Heuvel et al. 1992). This is because BHs are bright in X-rays only when they have close companion stars and binary periods of less than about 1 day.

Great effort has been made to discover a variety of BHs in binary stars (hereafter BH binaries). Many spectroscopic observations have reported BH binaries with periods of $1-100$ days (Liu et al. 2019; Thompson et al. 2019; Rivinius et al. 2020; Jayasinghe et al. 2021, 2022b; Lennon et al. 2022; Saracino et al. 2022). However, many concerns have been

[^0]raised regarding these reports (Abdul-Masih et al. 2020; Bodensteiner et al. 2020; El-Badry \& Quataert 2020; Eldridge et al. 2020; Irrgang et al. 2020; Safarzadeh et al. 2020; Shenar et al. 2020; Tanikawa et al. 2020; van den Heuvel \& Tauris 2020; El-Badry \& Quataert 2021; El-Badry et al. 2022a, 2022b; El-Badry \& Burdge 2022). Several BH binaries (Giesers et al. 2018; Shenar et al. 2022) still survive, despite such a harsh environment for BH binary searchers.

Gaia has monitored more than $10^{9}$ stars and their astrometric and spectroscopic motions during 34 months (Gaia Collaboration et al. 2016, 2018a, 2021, 2022a), and have published $\sim 3 \times 10^{5}$ astrometric and spectroscopic binary stars in total in Gaia Data Release 3 (GDR3; Holl et al. 2022a; Gaia Collaboration et al. 2022b; Holl et al. 2022b; Halbwachs et al. 2022). Before GDR3, many studies have predicted that will Gaia discover a large amount of compact objects in binary stars, such as white dwarfs (WDs), neutron stars (NSs), and BHs, from Gaia's astrometric data (Breivik et al. 2017; Mashian \& Loeb 2017; Kinugawa \& Yamaguchi 2018; Yalinewich et al. 2018; Yamaguchi et al. 2018; Andrews et al. 2019; Shahaf et al. 2019; Shao \& Li 2019; Shikauchi et al. 2020; Andrews et al. 2021; Chawla et al. 2022; Janssens et al. 2022; Shikauchi et al. 2022). Starting with Gaia Collaboration et al. (2022b), many research groups have searched for WD, NS, and BH binaries in spectroscopic binaries (Jayasinghe et al. 2022a; Fu et al. 2022; Gomel et al. 2022) and astrometric
binaries (Andrews et al. 2022; Chakrabarti et al. 2022; ElBadry et al. 2023a; Shahaf et al. 2023) just after GDR3.

GDR3 has presented several $10^{4}$ binary stars with both astrometric and spectroscopic data. However, previous studies have focused on either astrometric or spectroscopic data. In this paper, we first search for BH binaries from binary stars where both data sets are available, taking into account both astrometric and spectroscopic data. In other words, we first make a comparison between the astrometric and spectroscopic mass functions (see Equations (1) and (3), respectively) to search for BH binaries.

We eventually find a promising BH binary candidate whose source ID is GDR3 5870569352746779008 . After we posted this work to arXiv, El-Badry et al. (2023a) independently pointed out that this BH binary candidate is promising, and ElBadry et al. (2023b) confirmed it as a genuine BH binary by follow-up observations. This shows that our search is helpful and efficient to narrow down BH binary candidates. Although we recognize that El-Badry et al. (2023b) call it "Gaia BH2," we call it a "BH binary candidate" in this paper. This is not because we disagree with their confirmation, but because we regarded it as a BH binary candidate when we posted this work to arXiv (2022 September).

The structure of this paper is as follows. In Section 2, we describe how to select a sample of binary stars from GDR3, and how to list BH binary candidates. Finally, we find one BH binary candidate. In Section 3, we analyze the BH binary candidate in detail. In Section 4, we discuss the BH binary candidate, comparing it with BH binary candidates listed by previous studies. In Section 5, we summarize this paper.

## 2. Sample Selection

### 2.1. Search for $B H$ Binaries with $\mathrm{m}_{2}>3 \mathrm{M}_{\odot}$

We select GDR3 binary stars with astrometric and spectroscopic data (Gaia Collaboration et al. 2022b). There are three types of such binary stars. The orbital solutions of the first type are obtained from astrometric and spectroscopic data. They have an nss_solution_type name of "AstroSpectroSB1" in the nonsingle star tables of GDR3 (nss_two_body_orbit). We call them AstroSpectroSB1 binary stars. The second type has an orbital solution derived only from astrometric data, and additionally has a total amplitude in the radial-velocity time series called "rv_amplitude_robust". Such binary stars have an nss_solution_type name of "Orbital," and satisfy the following two conditions. First, they are bright stars; they have a Gaia GRVS magnitude less than and equal to 12 . Second, their radial velocities are computed more than twice. For the third type, binary stars have two nss_solution_type names of "Orbital" and "SB1" independently. Such binary stars also have an non_single_star value of 3 . Hereafter, the second and third types are collectively called Orbital binary stars simply. We can extract such a sample of binary stars from GDR3 with the following ADQL query:
select nss.*, gs.* from gaiadr3.nss_two_body_orbit as nss, gaiadr3.gaia_source as gs where nss.source_id=gs.source_id and (nss. nss_solution_type='AstroSpectroSB1' or (nss. nss_solution_type='Orbital' and gs.rv_amplitude_robust IS NOT NULL) or gs.non_single_ star=3)

Line numbers 5, 6-7, and 8 in the above ADQL query try to pick up the first, second, and third types, respectively.

However, line number 8 picks up binary stars not only of the third type but also many other binaries, for example, binary stars with nss_solution_type names of "acceleration7" and "SB1." We exclude them later. Finally, the total number of binary stars is 64,108 consisting of 33,467 "AstroSpectroSB1" and 30,641 "Orbital" binary stars, where the numbers of the second and third types are 30,629 and 12 , respectively.

We search for BH binary candidates from the above sample, using astrometric and spectroscopic mass functions ( $f_{\mathrm{m}, \text { astro }}$ and $f_{\text {m,spectro }}$, respectively). We express these mass functions as follows:

$$
\begin{align*}
f_{\mathrm{m}, \text { astro }} & =\left(m_{1}+m_{2}\right)\left|\frac{m_{2}}{m_{1}+m_{2}}-\frac{F_{2} / F_{1}}{1+F_{2} / F_{1}}\right|^{3}  \tag{1}\\
& =1\left(\frac{a_{1}}{\mathrm{mas}}\right)^{3}\left(\frac{\varpi}{\mathrm{mas}}\right)^{-3}\left(\frac{P}{\mathrm{yr}}\right)^{-2}\left[M_{\odot}\right] \tag{2}
\end{align*}
$$

and:

$$
\begin{align*}
f_{\mathrm{m}, \text { spectro }} & =\left(m_{1}+m_{2}\right)\left(\frac{m_{2}}{m_{1}+m_{2}}\right)^{3} \\
& =3.7931 \times 10^{-5}\left(\frac{K_{1}}{\mathrm{~km} \mathrm{~s}^{-1}}\right)^{3}\left(\frac{P}{\mathrm{yr}}\right), \tag{3}
\end{align*}
$$

$$
\begin{equation*}
\times\left(1-e^{2}\right)^{3 / 2} \sin ^{-3} i\left[M_{\odot}\right] \tag{4}
\end{equation*}
$$

where $m_{1}$ and $m_{2}$ are the primary and secondary stars of the binary star; $F_{2} / F_{1}$ is the flux ratio of the secondary star to the primary star; $a_{1}$ is the angular semimajor axis of the primary star; $K_{1}$ is the semiamplitude of the radial velocity of the primary star; and $\varpi, P, e$, and $i$ are the parallax, period, eccentricity, and inclination angle of the binary star, respectively. We define the primary star as the star observed by astrometry and spectroscopy, and the secondary star as the fainter star than the primary star. The secondary star is an unseen star if $F_{2} / F_{1}=0$. We can get $a_{1}, \varpi, P, e$, and $i$ from astrometry, and $K_{1}$ from spectroscopy. We have to remark that $f_{\mathrm{m}, \text { spectro }}$ is similar to but different from the spectroscopic mass function ordinarily defined (hereafter $\hat{f}_{\mathrm{m}, \text { spectro }}$ ), since we obtain $f_{\mathrm{m}, \text { spectro }}$ by dividing $\hat{f}_{\mathrm{m}, \text { spectro }}$ by $\sin ^{3} i$. We can know the inclination angle, $i$, thanks to astrometric observations, and thus mainly refer to $f_{\mathrm{m}, \text { spectro }}$, not $\hat{f}_{\mathrm{m}, \text { spectro }}$.

Practically, we calculate the $f_{\mathrm{m}, \text { spectro }}$ of AstroSpectrosB1 binary stars as

$$
\begin{equation*}
f_{\mathrm{m}, \text { spectro }}=\left[\left(\frac{C_{1}}{\mathrm{au}}\right)^{2}+\left(\frac{H_{1}}{\mathrm{au}}\right)^{2}\right]^{3 / 2}\left(\frac{P}{\mathrm{yr}}\right)^{-2} \sin ^{-3} i\left[M_{\odot}\right] \tag{5}
\end{equation*}
$$

where $C_{1}$ and $H_{1}$ are Thiele-Innes elements (Binnendijk 1960; Heintz 1978), derived by spectroscopic observations. On the other hand, we calculate $f_{\mathrm{m}, \text { spectro }}$ of Orbital binary stars, substituting half rv_amplitude_robust into $K_{1}$.


Figure 1. Scatterplots of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }}$ for AstroSpectroSB1 (top) and Orbital (bottom) binary stars. The color scale represents the square root of the relative density of binary stars. The shaded regions satisfy the two conditions of BH binary candidates expressed as Equations (6) and (7). The BH binary candidate found in this work (GDR3 5870569352746779008) is emphasized as a star in the top panel.

We regard binary stars as BH binary candidates if they satisfy the following two conditions:

$$
\begin{gather*}
0.5 \leqslant f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }} \leqslant 2 \\
f_{\mathrm{m}, \text { astro }} \geqslant 3 M_{\odot} \tag{7}
\end{gather*}
$$

We adopt the first condition expressed by Equation (6) for the following reason. When a binary star is a BH binary, the secondary star is an unseen star; hence, $F_{2} / F_{1}=0$. Substituting $F_{2} / F_{1}=0$ into Equation (1), we find $f_{\mathrm{m}, \text { astro }}=f_{\mathrm{m}, \text { spectro. }}$. Thus, BH binaries should satisfy $f_{\mathrm{m} \text {,astro }} \simeq f_{\mathrm{m}, \text { spectro }}$. By the second condition of Equation (7), we can select binary star candidates with $m_{2} \geqslant 3 M_{\odot}$ irrespective of $m_{1}$. Such binary stars are likely to be BH binaries, since the maximum mass of NSs is expected to be $\sim 2 M_{\odot}$ (Kalogera \& Baym 1996).

Figure 1 shows $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m} \text {,astro }}$ for all the samples. The shaded region in this figure corresponds to the two conditions imposed in this study (Equations (6) and (7)).

Table 1
Basic Parameters of the BH Binary Candidate

| Quantities | Values |
| :---: | :---: |
| (1) Source ID | 5870569352746779008 |
| (2) Orbital solution | AstroSpectroSB1 |
| (3) R.A. | 207.5697 |
| (4) decl. | -59.2390 |
| (5) Galactic longitude | 310.4031 |
| (6) Galactic latitude | 2.7765 |
| (7) Absolute magnitude in $G$ band ( $M_{\mathrm{G}}$ ) | 1.95 mag |
| (8) Extinction in $G$ band ( $A_{\mathrm{G}}$ ) | 0.5628 mag ( 0.70 mag ) |
| (9) BP - RP color | 1.49 mag |
| (10) Reddening of BP - RP color | 0.37 mag |
| (11) Surface gravity ( $\log g$, logg_gspphot) | 3.25 [cgs] |
| (12) [M/H] (mh_gspphot) | 0.0066 dex |
| (13) Goodness of fit | 3.07 |
| (14) Distance | $1164.41 \pm 25.16 \mathrm{pc}$ |
| (15) Period ( $P$ ) | $1352.22 \pm 45.81$ day |
| (16) Physical semimajor axis $\left(a_{1} / \varpi\right)$ | $4.5194 \pm 0.1305 \mathrm{au}$ |
| (17) Eccentricity (e) | $0.5323 \pm 0.0153$ |
| (18) Inclination (i) | $35.15 \pm 0.99$ |
| (19) Radial-velocity semiamplitude ( $K_{1}$ ) | $27.0 \pm 1.0 \mathrm{~km} \mathrm{~s}^{-1}$ |
| (20) Astrometric mass function ( $f_{\text {m,astro }}$ ) | $6.75 \pm 0.51 M_{\odot}$ |
| (21) Lower bound on $f_{\text {m,astro }}(99 \%)$ | $f_{\text {m,astro }}>5.68 M_{\odot}$ |
| (22) Spectroscopic mass function ( $f_{\text {m,spectro }}$ ) | $8.85 \pm 1.13 M_{\odot}$ |
| (23) Lower bound on $f_{\mathrm{m}, \text { spectro }}(99 \%)$ | $f_{\text {m,spectro }}>6.57 M_{\odot}$ |
| (24) Probability of $f_{\mathrm{m} \text {,spectro }}>f_{\text {m,astro }}$ | 95\% |
| (25) Probability of $f_{\mathrm{m} \text {,spectro }}<f_{\mathrm{m}, \text { astro }}$ | 5\% |

Note. From row 3 (R.A.) to 13 (goodness of fit) except for row 8 (extinction in $G$ band), we show the mean value in GDR3. For row 8 (extinction in $G$ band), the value is obtained from the EXPLORE G-Tomo scientific data application, and the value in the parentheses is obtained from the mean value in GDR3. From row 14 (distance) to 20 ( $\left.f_{\mathrm{m}, \text { astro }}\right)$ as well as in row $22\left(f_{\mathrm{m}, \text { spectro }}\right)$, we show the mean value and 1 standard deviation interval. In rows 21 and 23 , we show the $99 \%$ confidence level of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }}$, respectively. In rows 24 and 25 , we show the probabilities of $f_{\mathrm{m}, \text { spectro }}>f_{\mathrm{m} \text {,astro }}$ and $f_{\mathrm{m}, \text { spectro }}<f_{\mathrm{m} \text {,astro }}$, respectively (see Section 3 for more details).

Only one binary star satisfies these two conditions. Its basic parameters are summarized in Table 1. We analyze this BH binary candidate in the later sections.

In general, we have $f_{\mathrm{m} \text {,spectro }} \geqslant f_{\mathrm{m} \text {,astro }}$ for any binary star, which can be easily confirmed from the definitions in Equations (1) and (3). However, Figure 1 shows that the distribution of $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m} \text {,astro }}$ spreads under 1 . There can be two reasons for this. First, $f_{\mathrm{m}, \text { spectro }}$ is underestimated for the second type of binary stars. For these binary stars, we adopt rv_amplitude_robust for $K_{1}$ in Equation (4). However, the observed radial velocities may not fall at the right phase to sample fully the orbit's maximum and minimum radial velocities. Second, some of binary stars contain large errors of either $f_{\mathrm{m}, \text { spectro }}$ or $f_{\mathrm{m} \text {,astro }}$, while they have $f_{\mathrm{m}, \text { spectro }} \geqslant f_{\mathrm{m}, \text { astro }}$ in reality. In fact, such binary stars may hide BH binaries. However, in this paper, we conservatively select binary stars with $f_{\mathrm{m}, \text { spectro }} \simeq f_{\mathrm{m} \text {,astro }}$ as BH binary candidates. This is because the small discrepancy between $f_{\mathrm{m} \text {,spectro }}$ and $f_{\mathrm{m} \text {,astro }}$ is anticipated for a binary system in which the secondary star is much fainter than the primary $\operatorname{star}\left(F_{2} / F_{1} \simeq 0\right)$.

It is a bit strange that the $\log \left(f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }}\right)$ values are centered on zero for both the AstroSpectroSB1 and Orbital binary stars. Typically, binary stars should have luminous secondary stars (e.g., Sana et al. 2012), and thus


Figure 2. Distributions of the $\log f_{\mathrm{m} \text {, astro }}$ and $\log f_{\mathrm{m}, \text { spectro }}$ dispersions for the AstroSpectroSB1 binary stars. The red and blue dashed lines indicate the $\log f_{\mathrm{m}, \text { astro }}$ and $\log f_{\mathrm{m} \text {,spectro }}$ dispersions, respectively, for the BH binary candidate (GDR3 source ID 5870569352746779008 ).
should have $F_{2} / F_{1}$ close to 1 , and large $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m} \text {,astro }}$ (or small $f_{\mathrm{m}, \text { astro }}$ ). The reason for this discrepancy might be that Gaia preferentially selects binary stars with faint secondary stars.

Figure 2 shows the distributions of the $\log f_{\mathrm{m} \text {, astro }}$ and $\log f_{\mathrm{m}, \text { spectro }}$ dispersions for the AstroSpectroSB1 binary stars. In order to obtain these dispersions, we generate $10^{3}$ Monte Carlo random draws of the covariance matrix of the BH binary candidate in the GDR3 nss_two_body_orbit table. Note that the number of Monte Carlo random draws is sufficient, since the distributions for $10^{3}$ random draws are similar to those for $10^{2}$ random draws. We cannot calculate the $\log f_{\mathrm{m} \text {,spectro }}$ dispersions of the Orbital binary stars, since the covariance matrix does not include the data of rv_amplitude_robust. The $\log f_{\mathrm{m}, \text { spectro }}$ dispersions of the Orbital binary stars should be larger than those of the AstroSpectroSB1 binary stars. This is also the reason why the $\log \left(f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }}\right)$ values spread more widely for the Orbital binary stars than in the AstroSpectroSB1 binary stars. The peak of the $\log f_{\mathrm{m}, \text { spectro }}$ dispersion is at $\sim 0.2$. On the other hand, $\gtrsim 100$ binary stars have $\log f_{\mathrm{m} \text {,spectro }}$ dispersions $\gtrsim 1$. This should affect the presence of binary stars with $\log f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }}<0$.

If a binary star system is actually a triple star system, $f_{\mathrm{m}, \text { spectro }}$ will be significantly overestimated, and consequently $f_{\mathrm{m} \text {,spectro }}>f_{\mathrm{m}, \text { astro }}$ for the following reason. Astrometric observations are sensitive to the outer binary's motion: the relative motion between the inner binary and third star. On the other hand, spectroscopic observations are sensitive to the inner binary's motion, since its motion velocity is much larger than the outer binary's motion velocity. Thus, we will calculate $f_{\mathrm{m}, \text { spectro }}$ in Equation (4), using $P, e$, and $i$ of the outer binary and $K_{1}$ of the inner binary. This $f_{\mathrm{m}, \text { spectro }}$ will be larger than the actual $f_{\mathrm{m}, \text { spectro }}$ of both the inner and outer binaries. For obtaining the inner (outer) binary's $f_{\mathrm{m}, \text { spectro }}$, the adopted $P\left(K_{1}\right)$ is larger than the actual inner (outer) binary's. This may happen for the Orbital binary stars more frequently.

### 2.2. Some Comments on the Rejected Binaries

Before analysing the BH binary candidate in detail, we review our search. In particular, we focus on binary stars which
look like BH binaries at a glance, but which our search rejects. GDR3 provides the binary_masses table including the masses of primary and secondary stars estimated from PARSEC isochrone models ${ }^{9}$ (Bressan et al. 2012). We can obtain such binary stars with following ADQL query:
select nss.*, gs.*, bm.* from gaiadr3. nss_two_body_orbit as nss, gaiadr3.gaia_source as gs, gaiadr3.binary_masses as bm where gs.source_id=nss.source_id and bm. source_id=nss.source_id and (nss.nss_solution_type='AstroSpectroSB1' or (nss.nss_solution_type='Orbital' and gs. rv_amplitude_robust IS NOT NULL) or (gs. non_single_star=3))

We just add the binary_masses table to the ADQL query in Section 2.1. Note that our samples are the ones obtained with the ADQL query in Section 2.1 unless otherwise stated. Not all of our samples are listed in the binary_masses table, because the mass estimation is only applied to primary stars in the main sequence (MS) in the color-magnitude diagram. In the binary_masses table, there are six AstroSpectroSB1 and three Orbital binary stars containing secondary stars with $>3 M_{\odot}$. In spite of their secondary masses, none of them are regarded as BH binary candidates by our search.

As for the six AstroSpectroSB1 binary stars, they are rejected because all of them have too large $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }}$ ( $>10$ ). This means that, although these binary stars have MS primary stars with $1-2 M_{\odot}$, they have secondary stars with $>3$ $M_{\odot}$ and smaller (but nonzero) luminosities than the primary stars. It is difficult to interpret these binary stars as BH binaries. Thus, we remove them from our list of BH binary candidates. The three Orbital binary stars are ruled out, since they have too small $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m} \text {,astro }}(<0.01)$. Incomprehensibly, their $F_{2} / F_{1}$ values are negative. Astrometric or spectroscopic results might not be appropriate. In fact, all of them have large goodness-of-fit values ( $>5$ ), where the goodness of fit is expected to obey a normal distribution if the astrometric parameters are correctly derived. When Andrews et al. (2022) search for NS and BH binaries, they rule out binary stars with goodness-of-fit values more than 5 from NS and BH binary candidates.

The second condition expressed by Equation (7) may be too strict to complete a search for BH binaries from our sample. This condition means that the secondary mass is more than 3 $M_{\odot}$ for any primary masses. We convert this condition to $m_{2}>3 M_{\odot}$, where $m_{2}$ is drawn from the lower limit of $m_{2}$ (m2_lower) in the GDR3 binary_masses table. By this conversion, we can relax our search for BH binaries, since the secondary mass can be more than $3 M_{\odot}$ even for $f_{\mathrm{m} \text {,astro }}<3 M_{\odot}$ if the primary mass is larger than a certain value. However, we find no other BH binary candidate. Although the two conditions expressed by Equations (6) and (7) are slightly strict, we confirm that there is only one BH binary candidate (GDR3 source ID 5870569352746779008) in the GDR3 astrometric binary stars with spectroscopic data.

## 3. Analysis of the BH Candidate

We summarize the basic parameters of the BH binary candidate in Table 1. For the R.A., decl., BP - RP color, reddening of the $\mathrm{BP}-\mathrm{RP}$ color, $[\mathrm{M} / \mathrm{H}]$, and surface gravity

[^1]$(\log g)$, we adopt the mean values in the GDR3 gaia_source table. The galactic longitude and latitude are derived from the R.A. and decl.. We obtain the mean value of the extinction in $G$ band $\left(A_{\mathrm{G}}\right)$ from the EXPLORE G-Tomo scientific data application (Lallement et al. 2022; Vergely et al. 2022), ${ }^{10}$ while the value in the parentheses is the mean value from the GDR3 gaia_source table. Hereafter, we adopt the former value for the extinction. We obtain the goodness-of-fit value from the GDR3 nss_two_body_orbit table. In order to calculate the mean values and one standard deviation intervals of the distance, period $(P)$, physical semimajor axis ( $a_{1} / \varpi$ ), eccentricity (e), inclination ( $i$ ), radial-velocity semiamplitude $\left(K_{1}\right)$, astrometric mass function $\left(f_{\mathrm{m}, \text { astro }}\right)$, and spectroscopic mass function ( $f_{\mathrm{m}, \text { spectro }}$ ), we generate $10^{4}$ Monte Carlo random draws of the covariance matrix of the BH binary candidate in the GDR3 nss_two_body_orbit table. ${ }^{11}$ In this method, we also obtain $f_{\mathrm{m}, \text { astro }}>5.68 M_{\odot}$ and $f_{\mathrm{m}, \text { spectro }}>6.57$ $M_{\odot}$ at a probability of $99 \%$. Note that the distance is calculated from the parallax in the GDR3 nss_two_body_orbit table, not in the GDR3 gaia_source table. According to Gaia Collaboration et al. (2022b), the parallax in the former table is more accurate than in the latter table. We get the absolution magnitude in $G$ band ( $M_{\mathrm{G}}$ ) from the mean of apparent magnitude in the GDR3 gaia_source table, and the mean of the distance derived above.

The goodness-of-fit value, 3.07 , is relatively low, since Andrews et al. (2022) consider that NS and BH binary candidates should have a goodness-of-fit value greater than 5. Note that the goodness-of-fit value for reliable sources should be normally distributed with a mean of zero. Thus, we are not going to argue that the BH binary candidate is reliable only from the goodness-of-fit value. Nevertheless, we have to remark that the goodness-of-fit value is typical of AstroSpectroSB1 binary stars, as described later (see Figure 7). Although the goodness-of-fit value largely deviates from zero, it would not directly mean that this BH binary candidate is unreliable. We find that the ratios of the mean to standard deviation intervals are high for $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }}$ (13.2 and 7.83 , respectively). They should be relatively well measured. Additionally, the $\log f_{\mathrm{m} \text {,astro }}$ and $\log f_{\mathrm{m}, \text { spectro }}$ dispersions are small, compared to those of other AstroSpectroSB1 binary stars, as seen in Figure 2. This should be additional evidence that the parameters of this BH candidate are well measured. Moreover, at a probability of $99 \%, f_{\mathrm{m}, \text { astro }}>5.68 M_{\odot}$ and $f_{\mathrm{m}, \mathrm{spectro}}>6.75 M_{\odot}$. These values are unlikely to fall below 3 $M_{\odot}$. A concern is that $f_{\mathrm{m}, \text { spectro }}$ is systematically larger than $f_{\mathrm{m} \text {,astro, }}$, which we discuss in Section 4.

Figure 3 shows a color-magnitude diagram of the primary star of the BH binary candidate, and GDR3 stars whose absolute $G$-band magnitudes and BP-RP colors are well measured. MS and red giant branch (RGB) regions are defined as regions below and above the dashed line. The dashed line is expressed as

$$
M_{\mathrm{G}}= \begin{cases}3.14(\mathrm{BP}-\mathrm{RP})-0.43 & (\mathrm{BP}-\mathrm{RP}<1.41)  \tag{8}\\ 4 & \text { (otherwise) }\end{cases}
$$

[^2]

Figure 3. Color-magnitude diagram of stars in the GDR3 gaia_source table. These stars are filtered in the same way as those in Figure 6(c) of Gaia Collaboration et al. (2018b). The color scale represents the square root of the relative density of stars. The star and diamond points indicate the BH binary candidate (GDR3 source ID 5870569352746779008), where the star and diamond points are uncorrected and corrected for extinction and reddening, respectively. We define the regions of the MS and RGB stars below and above the dashed line, respectively. The line is expressed as Equation (8).

The first case of Equation (8) is the same as in Andrews et al. (2022). We induce the second case to avoid regarding lowmass MS stars as RGB stars. As seen in Figure 3, the primary star of the BH binary candidate is likely to be an RGB star. This is consistent with its small surface gravity $(\log g=3.25)$. The primary star indicated by the star point (not corrected for extinction and reddening) is redder than RGB stars in the color-magnitude diagram. It suffers from interstellar reddening, since it is located in the Galactic disk ( $b=2^{\circ} .7765$ ). In fact, the primary star indicated by the diamond point (corrected for extinction and reddening) is on the RGB.

Generally, BH binary candidates are thought dubious when their primary stars are RGB stars. This is because such primary stars can easily outshine their companion stars even if the companion stars are more massive than the primary stars. Moreover, it is difficult to estimate the masses of RGB stars in binary systems. Such RGB stars can be in so-called Algol-type systems (El-Badry et al. 2022b). They can be luminous but low mass (say $\sim 0.1 M_{\odot}$ ) if they experience mass transfer. These types of problems frequently happen for BH binary candidates with only spectroscopic data, or the spectroscopic mass functions, $\hat{f}_{\mathrm{m}, \text { spectro }}$ (not $f_{\mathrm{m} \text {,spectro }}$ ) and $\hat{f}_{\mathrm{m}, \text { spectro }}$ are $\sim 1 M_{\odot}$. In order to conclude that their secondary stars are $>3 M_{\odot}$ compact objects, we need to estimate the primary stars' masses and inclination angles of the binary stars. As an illustration, let us consider a spectroscopic binary characterized by $\hat{f}_{\mathrm{m} \text {,spectro }}=1 \quad M_{\odot}$ and inclination angle $i=60^{\circ}$ (from which we obtain $f_{\mathrm{m} \text {,spectro }}=1.54 M_{\odot}$ ). If the the primary star's mass is $1.2 M_{\odot}$, the secondary star's mass is $3 M_{\odot}$. In this case, the 3 $M_{\odot}$ secondary star is highly likely a BH . In contrast, if the the primary star's mass is $0.2 M_{\odot}$, the secondary star's mass is 1.9 $M_{\odot}$. In this case, we cannot exclude the possibility that the 1.9 $M_{\odot}$ secondary star is an MS star outshined by the primary RGB star. From this simple illustrative example, we can see that the


Figure 4. The absolute $G$-band magnitude of multiple-star systems with equalmass MS stars whose ages are $10^{7}, 10^{8}, 10^{9}$, and $10^{10} \mathrm{yr}$. The total mass of the multiple-star systems is $5.68 M_{\odot}$, the lower bound mass of the secondary star of the BH binary candidate at a probability of $99 \%$. The component mass and the number of stars are shown in the lower and upper $x$-axes, respectively. We show only MS stars defined in Equation (8). That is the reason why the curves of $10^{9}$ and $10^{10} \mathrm{yr}$ cut off in the middle. We obtain the absolute $G$-band magnitude and BP-RP color at each mass and age, using the PARSEC code (Bressan et al. 2012). The metallicity is set to solar, the same as the primary star of the BH binary candidate. It seems that there are no publicly available spectroscopic survey data that provide reliable metallicity for the primary star of our BH binary candidate. The dashed line indicates the absolute $G$-band magnitude of the primary star, which is corrected by $G$-band extinction. The dotted line indicates the absolute $G$-band magnitude of a star half as luminous as the primary star.
mass estimation of primary stars critically affects whether their secondary stars are BHs or not.

Fortunately, these types of problems do not happen for our BH binary candidate. We know the inclination angle $i$ of the binary star from the astrometric data, and get $f_{\mathrm{m} \text {,spectro }}$ in a model-independent way. Moreover, this BH binary candidate has $f_{\mathrm{m}, \text { astro }}>5.68 M_{\odot}$ and $f_{\mathrm{m}, \text { spectro }}>6.75 M_{\odot}$ at a probability of $99 \%$. The secondary mass is more than $5 M_{\odot}$, even if this BH binary candidate is an Algol-type system, or the primary RGB mass is close to zero. The primary RGB star cannot outshine the $>5 M_{\odot}$ secondary star even if the secondary star is in the MS phase, or the faintest among $5 M_{\odot}$ stars in any phases except a BH. This point is described in detail below. Thus, the secondary star is likely to be a BH .

We examine the possibility that the secondary star of the BH binary candidate may be a single object that is not a BH , or it is a multiple-star system. When the stellar mass is fixed, MS stars are the faintest objects except for stellar remnants like WDs, NSs, and BHs. If an MS star with the same mass as the secondary star is more luminous than the primary star, the possibility that the secondary star is a single object but not a BH can be ruled out. When the total mass of the multiple-star system is fixed, a multiple-star system with equal-mass MS stars is the least luminous. This is because MS stars become luminous more steeply as their masses increase. If an $n$-tuple star system with equal-mass MS stars has the same mass as the secondary star, and a larger luminosity than the primary star, the possibility that the secondary star is any $n$-tuple star systems can be rejected. Thus, we compare the luminosity of


Figure 5. Bottom left: scatterplots of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }}$ for RGB stars in AstroSpectroSB1. The color scale represents the square root of the relative density of binary stars. The contours indicate $\sigma$ levels of $1,2, \cdots$, and 7 from the inner to the outer. The shaded region is considered to calculate the $p$ values in Table 2. The $p$-values are calculated by a kernel-density estimate with the kernel bandwidth of Scott's rule (Scott 1992). The star point indicates the BH candidate (GDR3 source ID 5870569352746779008). It is not included in the samples with which the $p$-values are calculated. Top and right: $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }}$ distributions, respectively. The histograms indicate the sample distribution, and the curves indicate the projected distributions derived by the kernel-density estimate.
the primary star with the luminosities of a single MS star or multiple MS star systems with equal masses.

Figure 4 shows the absolute $G$-band magnitude of multiplestar systems with equal-mass MS stars. The total mass of the multiple-star systems is $5.68 M_{\odot}$, the lower bound mass of the secondary star of the BH binary candidate at a probability of $99 \%$. We can rule out single, binary, and triple stars with a total mass of $5.68 M_{\odot}$. They would outshine the primary star if they were the secondary star. A quadruple star system with each having a stellar mass of $1.4-1.5 M_{\odot}$ is as luminous as the primary star. However, such a quadruple star system should be detected by Gaia itself. A quintuple star system each with a stellar mass of $1.1 M_{\odot}$ has a luminosity that is twice as faint as the primary star, and might not be observed by Gaia. Except for multiple-star systems with MS stars, the secondary star can be a triple NS system or a quadruple WD star system, where the maximum masses of the NS and WD are about 2.0 and $1.4 M_{\odot}$, respectively. Such systems may be more interesting than a single BH , since they have never been discovered to our knowledge. In any case, the secondary star should be a quadruple or a higher-order star system in the case where it is not a single BH. Moreover, the size of the system should be more compact than the pericenter distance of the primary star, $\sim 2.4$ au. It is unclear that such multiple systems are stable under perturbations of the primary star.

In order to assess whether the BH binary candidate is coincidentally located on the $f_{\mathrm{m}, \text { astro }}-f_{\mathrm{m}, \text { astro }} / f_{\mathrm{m}, \text { spectro }}$ plane, we calculate the $p$-values of a $f_{\mathrm{m}, \text { astro }}-f_{\mathrm{m}, \text { astro }} / f_{\mathrm{m}, \text { spectro }}$ region around the BH binary candidate. We adopt a kernel-density estimate with a kernel bandwidth of Scott's rule (Scott 1992). The bandwidth is $N_{\text {sample }}^{-1 / 6}$, where $N_{\text {sample }}$ is the number of samples. At first, we select RGB primary stars from AstroSpectroSB1 as samples for the kernel-density

Table 2
$P$-values

| Sample | Number | $P$-value | $\sigma$ Level | Remark |
| :--- | :---: | :---: | :---: | :---: |
| All | 64,095 | $2.4 \times 10^{-12}$ | 7.0 |  |
| All in AstroSpectroSB1 | 33,466 | $9.1 \times 10^{-12}$ | 6.8 |  |
| Small errors in AstroSpectroSB1 | 28,188 | $1.0 \times 10^{-11}$ | 6.8 | Exclude samples with the top 10\% largest errors |
| Small errors in AstroSpectroSB1 | 17,614 | $1.1 \times 10^{-11}$ | 6.8 | Exclude samples with errors more than 0.2 in log-scale |
| RGBs in AstroSpectroSB1 | 9047 | $9.6 \times 10^{-12}$ | 6.1 | The same samples used in Figure 5 |
| Small errors for RGBs in AstroSpectroSB1 | 8626 | $7.5 \times 10^{-10}$ | 6.2 | Exclude samples with the top 10\% largest errors |
| Small errors for RGBs in AstroSpectroSB1 | 5395 | $1.2 \times 10^{-9}$ | 6.1 | Exclude samples with errors more than 0.2 in log-scale |

estimate. The number of samples is 9047 . Note that the BH binary candidate is excluded from the samples. Figure 5 shows the kernel-density contours of $1,2, \cdots$, and $7 \sigma$ levels from the inner to the outer. We calculate the $p$-value in the shaded region. The $p$-value is $9.6 \times 10^{-12}$, and the $\sigma$ level is 6.1 . The position of $f_{\mathrm{m} \text {,astro }}$ and $f_{\mathrm{m}, \text { astro }} / f_{\mathrm{m} \text {,spectro }}$ of the BH binary candidate is unlikely to be coincident.

We select samples for the kernel-density estimate in different ways in order to investigate whether the $p$-values depend on the choice of samples. We summarize the choices of samples and their results in Table 2. The first column indicates the choice of samples. Note that the BH binary candidate is not included in any choices. For "All," we choose all the samples selected in Section 2. For "All in AstroSpectroSB1," we choose all the samples in AstroSpectroSB1. For "RGBs in AstrospectroSB1," we extract only the RGB primary stars in the samples of "All in AstroSpectroSB1." These samples are shown in Figure 5. We also make samples, excluding samples with large errors of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m} \text {,spectro }}$ from "All in AstroSpectroSB1" and "RGBs in AstroSpectroSB1." We calculate the errors in the same way as the one standard deviation of the BH binary candidate in Table 1, where we generate $10^{3}$ Monte Carlo random draws for each sample for calculation cost savings. We adopt two cases to exclude samples. In the first case, we exclude $10 \%$ of the samples with the largest errors in either of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }}$. In the second case, we exclude samples with errors larger than 0.2 in logscale for either of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }}$. Note that 0.2 is similar to the bandwidth of the kernel-density estimate. In any cases, the $p$-values are small, and the $\sigma$ levels are high. The positions of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { astro }} / f_{\mathrm{m}, \text { spectro }}$ of the BH binary candidate are unlikely to be coincident, independent of the choices of samples for the kernel-density estimates.

We search for the BH binary candidate in several databases. The GDR3 variability table (Eyer et al. 2022) and the All-Sky Automated Survey for SuperNovae (ASAS-SN; Kochanek et al. 2017) do not include the BH binary candidate as a variable star. Its light curve is available on the ASAS-SN Photometry Database (Shappee et al. 2014; Jayasinghe et al. 2019). ${ }^{12}$ The BH binary candidate is observed in the $V$ and $g$ bands over $\sim 3000$ days. We do not find any periodic feature. The Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) has performed two high-cadence observations during about 30 days according to data downloaded from TESScut ${ }^{13}$ for the BH binary candidate. The duration is too short to detect its periodic variability due to its binary orbit, since it has a period of about 1000 days. The Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) also observed the BH

[^3]binary candidate over $\sim 4000$ days according to the ALLWISE Multiepoch Photometry Table ${ }^{14}$ and NEOWISE-R Single Exposure (L1b) Source Table. ${ }^{15}$ We do not recognize any periodic variability. At the time of 2022 September, the BH binary candidate is not listed in the following databases: SIMBAD, ${ }^{16}$ the ninth catalog of spectroscopic binary orbits (SB9; Pourbaix et al. 2004); RAdial Velocity Experiments (RAVE; Kunder et al. 2017); the Galactic Archaeology with HERMES (GALAH; Buder et al. 2021); the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) surveys (Cui et al. 2012); and the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski et al. 2017). High-energy telescopes, such as the Fermi Gamma-ray Space Telescope (Atwood et al. 2009), the Swift Burst Alert Telescope (BAT; Barthelmy et al. 2005) XMM-Newton (Strüder et al. 2001), the Chandra Observatory (Weisskopf et al. 2000), and the Galaxy Evolution Explorer (GALEX; Martin et al. 2005), have not observed it as far as we can see in Aladin lite. ${ }^{17}$ The ESO archive ${ }^{18}$ does not list it. In summary, we do not find any positive or negative evidence for the BH binary candidate.

## 4. Discussion

First, we compare the BH binary candidate with other BH binary candidates found in previous studies, and assess whether our BH binary candidate is similar to others rejected before. As described in Section 3, BH binary candidates tend to be rejected when their primary stars are RGB stars. It is difficult to estimate the masses of RGB stars, and such binary stars can be Algol-type systems in which the primary stars are low mass (say $\sim 0.1 \quad M_{\odot}$ ). Since such BH binary candidates have $\hat{f}_{\mathrm{m} \text {,spectro }} \sim 1 \quad M_{\odot}$, the mass estimate of RGB stars severely affects the secondary mass. However, our BH binary candidate has $f_{\mathrm{m} \text {,astro }}>5.68 M_{\odot}$ and $f_{\mathrm{m} \text {,spectro }}>6.75 M_{\odot}$ at a probability of $99 \%$. In this case, the secondary mass is more than $\sim 5 M_{\odot}$ even if the primary mass is nearly zero. Note that the secondary mass increases monotonically, with the primary mass increasing when $f_{\mathrm{m}, \text { astro }}$ or $f_{\mathrm{m}, \text { spectro }}$ is fixed. Thus, the secondary star is likely to be a BH , even if the BH binary candidate is an Algoltype system.

Gaia Collaboration et al. (2022b) listed up BH binary candidates with $\sim 2 M_{\odot}$ MS stars and $\sim 3 M_{\odot}$ BHs. However, El-Badry \& Rix (2022) pointed out the possibility that they are

[^4]

Figure 6. Comparison of the orbital parameters (period, eccentricity, radial-velocity semiamplitude, and $\hat{f}_{\mathrm{m}, \text { spectro }}$ ) between GDR 3 and SB9. The triangle, circle, and star points indicate objects from GDR3 SB1, AstroSpectroSB1 with a period of $\leqslant 10^{3}$ days, and AstroSpectroSB1 with a period of $>10^{3}$ days, respectively. The dashed lines show the mean values of the orbital parameters of the BH binary candidate (GDR3 source ID 5870569352746779008).

Algol-type systems consisting of $\sim 0.2 M_{\odot}$ stripped stars and $\sim 2$ $M_{\odot}$ MS stars. The reason for this discrepancy is as follows. Gaia Collaboration et al. (2022b) thought that $\sim 2 M_{\odot}$ MS stars dominate the luminosity (photometry) and radial-velocity motion (spectroscopy) of the binary stars. On the other hand, El-Badry \& Rix (2022) claimed that $\sim 2 M_{\odot}$ MS stars dominate the luminosity, while $\sim 0.2 M_{\odot}$ stripped stars dominate the radialvelocity motion. This interpretation better explains their spectral energy distributions and spectroscopic mass functions ( $\hat{f}_{\mathrm{m}, \text { spectro }} \sim 1.5 \quad M_{\odot}$ ) more naturally. We do not expect that a similar situation applies to our BH binary candidate for the following reason. If a hidden star dominates the radial-velocity motion, we replace $m_{2}$ with $m_{1}$ in Equation (3). Since $f_{\mathrm{m}, \text { astro }} \sim f_{\mathrm{m}, \text { spectro }}$, we obtain $m_{1}=4 f_{\mathrm{m}, \text { astro }}\left(1+F_{2} / F_{1}\right)^{2} \quad M_{\odot}$ and $m_{2}=4 f_{\text {m, astro }}\left(1+F_{2} / F_{1}\right)^{2}\left(1+2 F_{2} / F_{1}\right) \quad M_{\odot}$. Thus, the RGB primary mass should be at least $4 f_{\text {m,astro }}\left(\sim 23 M_{\odot}\right)$. However, its luminosity requires its mass to be much less than $23 M_{\odot}$. Thus, a hidden star does not dominate the radial-velocity motion of our BH binary candidate in contrary to the BH binary candidates in Table 10 of Gaia Collaboration et al. (2022b).

Gaia Collaboration et al. (2022b) also show another table of BH binary candidates (their Table 9) in which the BH binary candidates belong to SB1, and have high $\hat{f}_{\mathrm{m}, \text { spectro }}\left(>3 M_{\odot}\right)$. Hereafter, we call them "Gaia's Table 9 candidates." Although these candidates have secondary stars with more than $3 M_{\odot}$ for any primary mass, Gaia Collaboration et al. (2022b) cannot rule out that the secondary stars consist of multiple-star systems, similar to our description in Section 3. We remark that our BH candidate is better constrained than all of Gaia's Table 9 candidates. Our BH binary candidate has a larger mass function and smaller luminosity than Gaia's Table 9 candidates except for GDR3 source IDs 4661290764764683776 and 5863 544023161862144. GDR3 source ID 4661290764764683776 has a high $\hat{f}_{\text {m, spectro }}\left(=13.67 M_{\odot}\right)$; however, its primary star has a high luminosity, with -6.707 mag in $G$ band. Since the primary star can be more luminous than a $\sim 13 M_{\odot}$ MS star, it
is difficult to confirm that the secondary star is a BH. GDR3 source ID 5863544023161862144 shows eclipses, and consequently its secondary should not be a BH (Gaia Collaboration et al. 2022b). In summary, we can easily rule out the possibility that the secondary star of our BH candidate consists of a multiple-star system.

Pourbaix et al. (2022) and Jayasinghe et al. (2022a) compared the orbital parameters in GDR3 with those in SB9 (Pourbaix et al. 2004), in particular for spectroscopic binary stars with either component being parameterized (SB1). They found that Gaia's and SB9's periods are inconsistent for periods of more than $10^{3}$ days in SB9. Since they did not investigate AstroSpectroSB1, we investigate both of SB1 and AstroSpectroSB1 here. We find 304 SB1 and 109 AstroSpectroSB1 objects in common between GDR3 and SB9. Our BH binary candidate is not included in SB9 as described in the previous section. In Figure 6, we make a comparison between the orbital parameters of the binary stars in GDR3 and SB9. Note that the $x$-axes in Figure 6 adopt GDR3 values, while Pourbaix et al. (2022) and Jayasinghe et al. (2022a) adopt SB9 values for the $x$-axes in their Figure 7.41 and Figure 6, respectively. Similar to Pourbaix et al. (2022) and Jayasinghe et al. (2022a), we find that the periods in GDR3 are largely different from those in SB9 for SB1 objects with periods of more than $10^{3}$ days. However, for AstroSpectroSB1, their periods do not deviate up to periods of a few $10^{3}$ days. The other parameters in GDR3 are also in good agreement with those in SB9 for AstroSpectroSB1, in particular around the mean values of the orbital parameters of the BH binary candidate. This does not directly show that the spectroscopic data of the BH binary candidate are reliable, since most of the binary stars in SB9 are brighter than our BH binary candidate. Nevertheless, this means that the GDR3 values of AstroSpectroSB1 binary stars may be reliable even if the binary stars have periods of a few $10^{3}$ days.

Bashi et al. (2022) compared GDR3 SB1 with the database of LAMOST (Cui et al. 2012) and GALAH (Buder et al. 2021),


Figure 7. The ratio of $f_{\text {m,spectro }}$ to $f_{\text {m,astro }}$ as a function of goodness-of-fit value for AstroSpectroSB1 (top) and Orbital (bottom) binary stars. The color scale represents the square root of the relative density of binary stars. The star point indicates the BH binary candidate (GDR3 source ID $5870569352746779008)$.
and found that GDR3 SB1 objects with periods less than $10^{1.5}$ days may be refuted. Although our BH binary candidate belongs to AstroSpectroSB1 (not to SB1), it has a period of $\gtrsim 10^{3}$ days, much larger than $10^{1.5}$ days. Our BH binary candidate may not be refuted by the criteria of Bashi et al. (2022).

Andrews et al. (2022) and Shahaf et al. (2023) independently presented lists of NS and BH binary candidates in GDR3. Their lists do not include our BH binary candidate. This is because they focus on binary stars with primary MS stars. The masses of MS stars can be estimated less model dependently than those of RGB stars. The masses and natures of secondary stars can be derived robustly. Thus, they avoided binary stars with primary RGB stars. On the other hand, although the primary star of our BH binary candidate is an RGB star, we can call it a "BH binary candidate," because its $f_{\mathrm{m} \text {,astro }}$ and $f_{\mathrm{m}, \text { spectro }}$ are high: $\gtrsim 5.68$ and $6.75 M_{\odot}$, respectively, at a probability of $99 \%$. Its secondary mass is more than $5 M_{\odot}$, regardless of the primary RGB mass.

Conversely, we examine the lists of Andrews et al. (2022) and Shahaf et al. (2023) using our conditions. We focus on binary stars with $m_{2}>2 M_{\odot}$ in their lists. Note that the maximum NS mass can be $\sim 2 M_{\odot}$. Our sample selected in Section 2 does not include the BH binary candidates in Andrews et al. (2022)'s list. The candidates do not have spectroscopic data. This may be partly because astrometric binary stars with spectroscopic data ( i.e., our sample) have systematically large goodness-of-fit values. Figure 7 shows that the goodness-of-fit values in AstroSpectroSB1 and Orbital are centered at $\sim 3$ and $\sim 5$, respectively. Actually, this can be seen in the middle panel of Figure 4 in Andrews et al. (2022). Their Figure 4 includes all the Orbital binary stars with and without spectroscopic data, and indicates a second peak around the goodness-of-fit value of $\sim 5$. The second peak should consist of Orbital binary stars with spectroscopic data. We do not know the reason for this systematic upward shift. We have to remark that bright binary stars ( $G$-band magnitudes $<13$ ), i.e., those with spectroscopic data, have systematically higher goodness-of-fit values, while faint binary stars ( $G$-band magnitudes $>13$ ) typically have lower goodness-of-fit values. ${ }^{19}$ In any case, our sample does not include the list of

[^5]Andrews et al. (2022), because they avoid including binary stars with goodness-of-fit values of more than 5 in their list.

Our sample includes Shanaf et al. (2023)'s three BH binary candidates (GDR3 source IDs: 3263804373319076480, 3509370326763016704 , and 6281177228434199296 ). However, we do not list them up as BH binary candidates. This is because their $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m} \text {,astro }}$ are small $(0.25,0.0053$, and 0.0017 , respectively), based on our first condition as seen in Equation (6). We do not intend to reject the three BH candidates completely, however. The three BH candidates may suffer from large errors in their spectroscopic data, and consequently have small $f_{\mathrm{m}, \text { spectro }} / f_{\mathrm{m}, \text { astro }}$. We suspect this possibility, because two of the three BH candidates are not included in the AstroSpectroSB1 binary stars despite the fact that they have spectroscopic data. Our sample selected in Section 2 does not include the other five BH binary candidates because of the absence of spectroscopic data.
A few days after we posted this work on arXiv, El-Badry et al. (2023a) reported one promising BH binary candidate different from our BH binary candidate. They made follow-up spectroscopic observations, and showed that Gaia's astrometric data are consistent with their spectroscopic data. Since their BH binary candidate has a shorter period (185.6 days) than our binary candidate ( 1352.22 days), they finished their follow-up observation in a short period of time. They also mentioned our BH binary candidate, and did not conclude whether our BH binary candidate is genuine because of the absence of follow-up spectroscopic observations. Their argument is in good agreement with ours. Note that we analyze our BH binary candidate in detail.
Several BH binary candidates can be rejected for exceptional reasons. Although Gaia Collaboration et al. (2022b) found that GDR3 source ID 2006840790676091776 has a high $\hat{f}_{\mathrm{m}, \text { spectro }}$, they did not include it in their list of BH binary candidates. This is because it is close to a bright star, whose apparent magnitude is 3.86 mag in $G$ band. There are no such bright stars close to our BH binary candidate. Any nearby stars have apparent magnitudes of at least 13 mag in $G$ band. The reason for this rejection cannot be applied to our BH binary candidate. Andrews et al. (2022) removed GDR3 source ID $4373465352415301632,{ }^{20}$ since its period ( $\sim 186$ days) is roughly 3 times Gaia's scanning period ( 63 days). Our BH binary candidate has a period of 1352 days, not an integer multiple of Gaia's scanning period.
Hereafter, we discuss several concerns. First of all, we mostly rely on GDR3 astrometric and spectroscopic data, which are already largely processed. We do not assess the correctness of the data of our BH binary candidate. Aside from this, we find that the BH binary candidate has $f_{\mathrm{m}, \text { spectro }}>f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m} \text {,spectro }}<f_{\mathrm{m} \text {,astro }}$ at probabilities of 95 and $5 \%$, respectively (see Table 1). Although $f_{\mathrm{m} \text {,spectro }}=f_{\mathrm{m} \text {,astro }}$ is possible, $f_{\mathrm{m}, \text { spectro }}$ is always larger than $f_{\mathrm{m} \text {,astro }}$ in the $1 \sigma$-level region seen in Figure 8. For comparison, we calculate the probabilities of $f_{\mathrm{m}, \text { spectro }}>f_{\mathrm{m} \text {,astro }}$ and $f_{\mathrm{m}, \text { spectro }}<f_{\mathrm{m}, \text { astro }}$ for GDR3 source ID 5136025521527939072 , which is in AstroSpectroSB1, and suggested as a NS binary candidate by Gaia Collaboration et al. (2022b). ${ }^{21}$ They are $72 \%$ and $28 \%$, respectively. Both $f_{\mathrm{m}, \text { spectro }}>f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }}<f_{\mathrm{m}, \text { astro }}$ are in the $1 \sigma$-level region, in contrast to our BH binary candidate. The $f_{\mathrm{m}, \text { spectro }}$ and $f_{\mathrm{m} \text {,astro }}$ of our BH binary candidate are not as similar as

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Figure 8. Bottom left: two-dimensional probability distributions of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }}$ for the BH binary candidate (GDR3 source ID 5870569352746779008 ). The cross point means the typical values of $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }}$. The contours indicate $\sigma$ levels of 1,2 , and 3 from the inner to the outer. The dashed line shows $f_{\mathrm{m} \text {,astro }}=f_{\mathrm{m}, \text { spectro. }}$. Top and right: the $f_{\mathrm{m}, \text { astro }}$ and $f_{\mathrm{m}, \text { spectro }}$ distributions, respectively.
those of GDR3 source ID 5136025521527939072. Nevertheless, we may regard $f_{\mathrm{m}, \text { spectro }}=f_{\mathrm{m} \text {,astro }}$, since our BH binary candidate may contain some systematic errors in either the spectroscopic or astrometric data.

Another concern is that the primary star of the BH binary candidate is an RGB star. Theoretical studies (e.g., Shikauchi et al. 2020, 2022) expected that a BH binary with a $\gtrsim 10 M_{\odot}$ MS primary star is likely to be found first (but see also Shikauchi et al. 2023). This is because such MS stars are bright, and can be observed even if they are distant. Moreover, they are longer lived than RGB stars with similar masses. However, GDR3 does not present the orbital parameters of binary stars with $\gtrsim 10 M_{\odot}$ MS primary stars in AstrospectroSB1 or Orbital according to the GDR3 binary_masses table obtained with the ADQL query in Section 2.2. We do not know the reason for the absence of such binary stars in GDR3. Nevertheless, when there are no such binary stars, it may be natural that a BH binary with an RGB star is first discovered.

We need two types of follow-up observations in order to assess if the BH binary candidate is true or not. The first type should be spectroscopic observations to verify the GDR3 spectroscopic data, and to perform spectral disentangling of the BH binary candidate similar to El-Badry \& Rix (2022). The second type should be deep photometric observations. Such observations could constrain whether the secondary star is a BH , or consists of multiple stars. We remark that El-Badry et al. (2023b) have carried out these follow-up observations, and confirmed it as a genuine BH binary, called Gaia BH2. This demonstrates that these follow-up observations would be important for confirming or refuting future BH candidates, which may be discovered by our search methodology in upcoming Gaia data.

## 5. Summary

We first search for BH binary candidates from astrometric binary stars with spectroscopic data in GDR3. From a sample of 64,108 binary stars, we find one BH binary candidate. The GDR3 source ID is 5870569352746779008 . Since its primary


Figure 9. Predicted radial velocities of the BH binary candidate (GDR3 source ID 5136025521527939072), based on GDR3. The black curve can be obtained from typical values in GDR3. We generate cyan curves from $10^{2}$ Monte Carlo random draws, using the covariance matrix. The radial-velocity amplitude is larger and the turnover time spreads more widely than those in the upper panel of Figure 3 in El-Badry et al. (2023b), because we do not adopt any explicit link between the spectroscopic and astrometric Thiele-Innes parameters.
star is an RGB star, we cannot estimate the mass of the primary RGB star. However, because of its high astrometric and spectroscopic mass function $\left(f_{\mathrm{m}, \text { astro }}>5.68 \quad M_{\odot} \quad\right.$ and $f_{\mathrm{m}, \text { spectro }}>6.75 M_{\odot}$ at a probability of $99 \%$ ), the secondary star should have more than $5 M_{\odot}$, and is likely to be a BH , regardless of the primary mass. If the secondary star is not a BH , it must be a quadruple or higher-order multiple-star system with a total mass of $5.68 M_{\odot}$. To rule out the possibility that it is a multiple-star system, we need deep photometric observations. Rather, if it is a quadruple or higher-order multiple-star system, long-term observation may find modulation of the primary's orbit (e.g., Hayashi \& Suto 2020; Hayashi et al. 2020; Liu et al. 2022).

The weakness of this paper is that our conclusion entirely relies on Gaia DR3. In particular, our BH binary candidate has a period of $\sim 1300$ days, more than a period of 34 months of the Gaia DR3 data collection. Our conclusion has to be confirmed by follow-up observations. For example, we need the time evolution of the radial velocity of our BH binary candidate similar to that of Gaia BH1 obtained by El-Badry et al. (2023a). Figure 9 shows the predicted radial velocities of the BH binary candidate. Eventually, El-Badry et al. (2023b) have confirmed the radial-velocity variability of our candidate, by observing it $\sim 30$ times from the last half of 2022 to the beginning of 2023, when the radial velocities had steeply decreased.

Previously, RGB stars harboring BHs have not been searched for because of the difficulty of estimating the masses of RGB stars (and thus BHs). However, our tentative discovery in this paper encourages us to explore not only BHs orbiting around MS stars but also BHs orbiting around RGB stars in future data releases of Gaia.

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Software: Matplotlib (Hunter 2007); NumPy (van der Walt et al. 2011); Astropy (Astropy Collaboration et al. 2013); SciPy (Virtanen et al. 2020).

## ORCID iDs

Ataru Tanikawa © https:// orcid.org/0000-0002-8461-5517 Kohei Hattori (10) https:// orcid.org/0000-0001-6924-8862 Norita Kawanaka (1) https://orcid.org/0000-0001-8181-7511 Tomoya Kinugawa (0) https://orcid.org/0000-0002-3033-4576 Minori Shikauchi © https://orcid.org/0000-0002-3561-8658
Daichi Tsuna (1) https:// orcid.org/0000-0002-6347-3089

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[^1]:    9 http://stev.oapd.inaf.it/cgi-bin/cmd

[^2]:    ${ }^{10}$ https://explore-platform.eu/
    ${ }^{11}$ The number of Monte Carlo random draws is sufficiently large, since the results are similar if we adopt $10^{3}$ for the number of random draws.

[^3]:    $12 \mathrm{https}: / /$ asas-sn.osu.edu/photometry
    ${ }^{13}$ https://mast.stsci.edu/tesscut/

[^4]:    14 https://irsa.ipac.caltech.edu/cgi-bin/Gator/nph-scan? submit $=$ Select\&projshort $=$ WISE
    ${ }^{15} \mathrm{http}: / /$ irsa.ipac.caltech.edu/cgi-bin/Gator/nph-scan? submit $=$ Select\&projshort $=$ WISE
    16 http://simbad.cds.unistra.fr/simbad/
    ${ }^{17} \mathrm{https}$ ://aladin.u-strasbg.fr/AladinLite/
    ${ }^{18} \mathrm{http}: / /$ archive.eso.org/scienceportal/home

[^5]:    ${ }^{19}$ An exact value of 13 is obtained by El-Badry et al. (2023b).

[^6]:    ${ }^{20}$ This object is later confirmed as a BH binary (also known as Gaia BH1) by El-Badry et al. (2023a).
    ${ }^{21}$ The NS binary candidate is more likely to be a WD binary according to ElBadry et al. (2023a).

