# On the detection of emission near the event horizons of accreting stellar-mass black holes

L. Chmyreva [1] G. Beskin [1,2]

[1]Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhny Arkhyz, 369167, Russia

[2]Kazan Federal University, 18 Kremlyovskaya St, Kazan 420008, Russia

## Abstract

We discuss the possibility of detecting signs of the existence of stellar-mass black hole (BH) event horizons in the emission of interstellar gas accreting on them. We consider a sample of invisible compact objects detected as companions of Main Sequence stars in wide binaries. Theoretical luminosities and accretion rates of the interstellar gas were obtained within the framework of the spherical accretion model. BH velocities estimated from binary system dynamics, as well as the density of the surrounding ISM were used in the calculations. Based on the sensitivity data of existing and projected ground-based and space-based telescopes (JWST, GMT, TMT, ELT, MILLIMETRON), we estimated of the possibility of direct detection of both stationary and variable halo emission around the BHs.

## Introduction

According to current evolutionary predictions, the number of isolated stellar-mass black holes (BHs) in our Galaxy reaches $10^8$ [1]. Detecting manifestations of their event horizons, and therefore proving their existence, is very important: horizons are a generic feature of all BHs [2]. Direct high temporal resolution observations of their interaction with the surrounding medium (flares generated by beams of electrons in the direct vicinity of a BH) would allow us to obtain information on the structure of space-time near a BH. Such data can only be obtained for an isolated BH: in this case the accretion rate is low and the horizon is not obscured by the accreting matter.

However, detecting isolated black holes is very difficult in comparison with those that are members of X-ray binaries and whose masses can be estimated. At the same time, in the case of detached binaries, when the separation between the companions is sufficient and no interaction takes place between them, a BH would accrete matter as a single object, unaffected by the primary star. For our purpose, such BHs can be considered as isolated, and accretion onto an isolated BH, regardless of its metrics, is usually spherical. Luminosity for this type of accretion remains almost constant in a wide range of frequencies ($10^{14}$–$10^{20}$ Hz). A BH would exhibit a featureless spectrum and variable emission with an amplitude ranging from fractions of a percent to ten percent; the duration of individual flares would be $10^{-6}$ to $10^{-3}$ s [3, 4, 5, 6].

In this work we consider a sample of wide binaries with no Roche lobe overflow, hosting invisible compact companions, and estimate their theoretical luminosities in an assumption of spherical accretion and discuss the possibility of their direct detection by existing and future instruments.

## Sample Binaries and Calculations

Several non-interacting binaries comprising a compact object and a main sequence star were recently reported by various authors ([7, 8, 9, 10, 11, 12, 13]) based on Gaia DR3[a] data. For our analysis, we selected 17 wide non-interacting pairs with compact objects whose masses suggest they might be BHs. Some lower-mass compact objects that may be neutron stars were also considered, if their mass uncertainties allowed for the possibility of these object being more massive. The primary objects in the sample binaries are mostly bright ($m_V \sim 12-17$) stars of roughly solar mass, with several OB stars. We excluded candidates with suspected accretion disks and interaction between the components, leaving a sample of 10 systems.

The accretion rate $\dot{m}$ onto a BH and luminosity $L$ of the halo around it are determined by its mass, ISM density, and velocity relative to the surrounding gas ([14, 3, 15]):

$$L \propto M_{10}^3 n^2 (V^2 + c_s^2)_{16}^{-3} \ \text{erg s}^{-1}, \tag{1}$$

where $M_{10}$ is the BH mass in units of $10M_\odot$, $n$ is the ISM density in cm$^{-3}$, and $V$ and $c_s$ are the total BH velocity and sound speed normalized to $16$ km s$^{-1}$. Using the data available on the orbital parameters of the sample systems, we estimated the interval of acceptable total space velocities of the BHs as a combination of their minimum and maximum Keplerian orbital speed $V_{max}^{orb} = \frac{2\pi a}{P}\sqrt{\frac{1+e}{1-e}}$ and $V_{min}^{orb} = \frac{2\pi a}{P}\sqrt{\frac{1-e}{1+e}}$, where $P$ is the period of the system, $a$ is the semi-major axis, and $e$ is the eccentricity, and the system center-of-mass velocity $V_{COM}$ derived from the observed radial velocity of the primary star and its transverse velocity determined from its proper motion and distance: $V_{tr} = 4.74D\sqrt{(\mu_l \cos b)^2 + \mu_b{}^2}$. The local ISM densities were estimated from the G-Tomo[b] Galactic extinction maps as $n = \frac{dN_H}{dD}$, where $N_H$ is the hydrogen column density. Unlike isolated BHs with no influence from nearby stars, in the case of binary systems, accretion may be affected by the stellar winds from the primary companions. They were taken into account by assuming spherically-symmetric wind from a star of the corresponding spectral type. Wind speed was estimated as a parabolic velocity $V_0 \sim \alpha\sqrt{\frac{2GM}{R_0}}$, where the parameter $\alpha$ depends on the stellar type. The wind would contribute the value $\dot{M} = G^2 M_{BH}^2 \dot{M}_{wind}/V_0^4 a^2$ to the accretion onto a BH, where $\dot{M}_{wind}$ is the wind mass-loss rate of the primary star. The contribution from the winds turned out to be negligibly small in most cases. We did not consider the general galactic gas velocities, as they are below the uncertainty level of our BH velocity estimates. The densities were then used to determine the temperatures and sounds speeds in the surrounding gas.

## Results and Discussion

The resulting luminosities, accretion rates, and expected visual magnitudes are presented in **Table 1**. The velocities derived for the compact companions are the parameters that contribute the most to the high uncertainty in luminosity and accretion rate. Calculations have shown that most of the sources, if they are indeed BHs, are predictably faint - so far, none of the considered objects have been directly detected in observations. This is well demonstrated in **Figure 1**, which shows the derived spectral energy distribution for the first source in the sample, the famous Gaia DR3 4373465352415301632 known as Gaia BH1. It is a nearby, relatively large compact object with a mass of $\sim 10M_\odot$, located at $\sim 480$ pc with a Solar-type star orbiting it. And while its parameters are well-studied, observing its manifestations directly seems unlikely at present as its estimated luminosity, even with the given uncertainties, is below the sensitivity levels of current and projected telescopes even in the absence of a bright primary. However, several sample sources may be within the sensitivity range of instruments both already operating and planned (e.g., JWST, GMT, MILLIMETRON, TMT, ELT). In particular Gaia DR3 4314242838679237120, 3263804373319076480, and 5870569352746779008 show promise in that regard. The former object has a high velocity uncertainty, with only the lower estimate available and is therefore likely much fainter than the upper limit calculated in this paper. Gaia DR3 3263804373319076480 is a close object at $\sim 290$ pc and has a good chance of being detected, and the last source has a high mass - enough to rule out its being a neutron star. These sources will be studied in detail in our future work.

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[a] `https://www.cosmos.esa.int/web/gaia/dr3`

[b] `https://explore-platform.eu/sda/g-tomo`

**Figure 1**. Theoretical spectrum of the black hole in the Gaia DR3 4373465352415301632 binary system. Its parameters are listed in the top part of the figure. The flux density in Jy is shown by the black dashed curve as a function of frequency in Hz. The gray region shows the full uncertainty range corresponding to the acceptable parameter intervals for the object and interstellar medium. The limiting sensitivities of the current and planned observing missions in the optical, radio and near-IR spectral regions are shown in different colors listed in the bottom part of the figure.

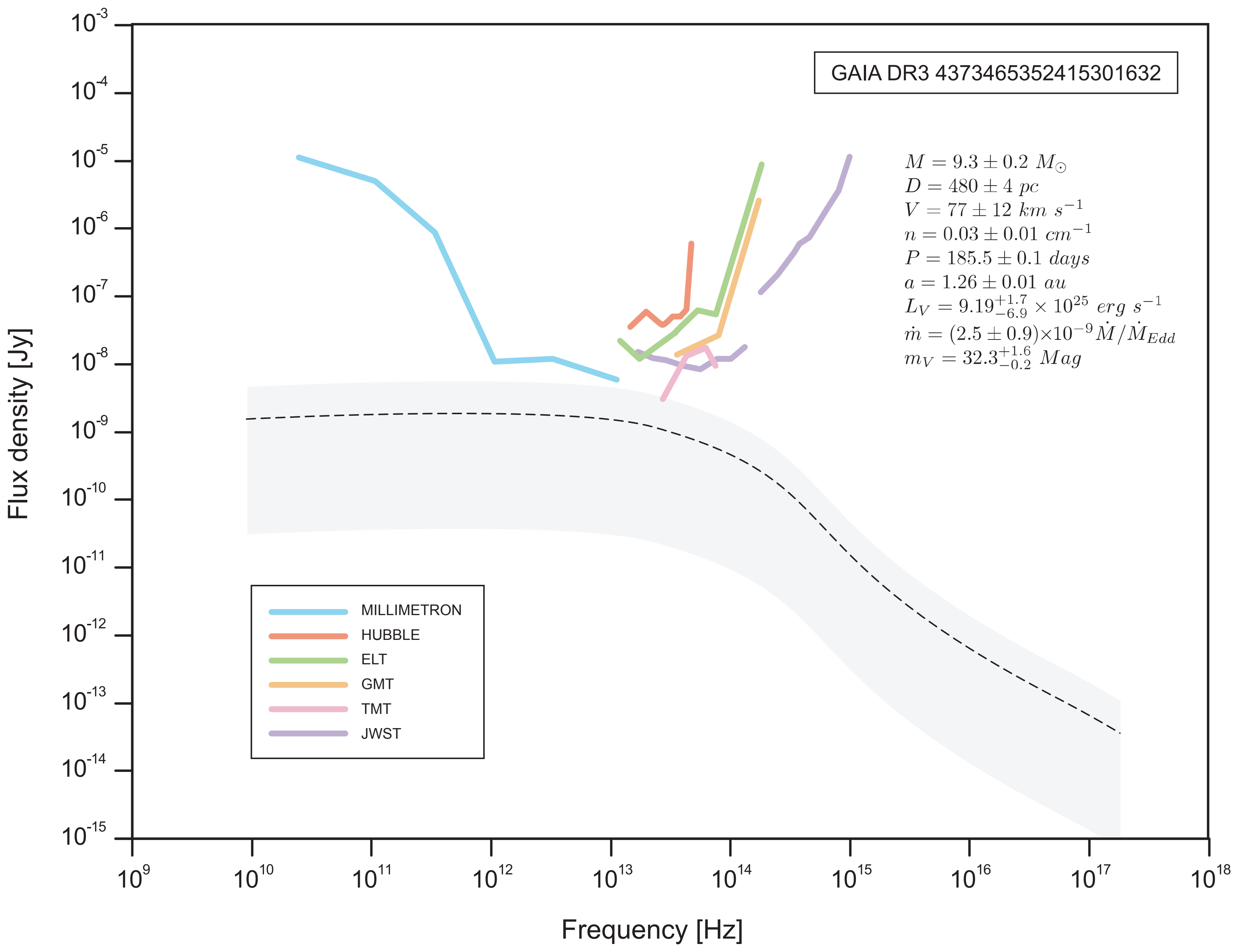

**Table 1**. Parameters of the compact companions: luminosities, accretion rates, visual magnitudes, masses, distances, and velocities

| *Source ID*<br>*Gaia DR3* | $L$<br>*erg s*$^{-1}$ | $\dot{m}$<br>$\dot{M}/\dot{M}_{Edd}$ | $m_V$<br>*Mag* | $M$<br>M$_\odot$ | $D$<br>*pc* | $V$<br>*km s*$^{-1}$ |
|---|---|---|---|---|---|---|
| 4373465352415301632 | $(6.6 \pm 4.4) \times 10^{25}$ | $(2.5 \pm 0.9) \times 10^{-9}$ | $32.3^{+1.6}_{-0.2}$ | $9.3 \pm 0.2$ | $480 \pm 4$ | $77 \pm 12$ |
| 4314242838679237120 | $(7.5 \pm 7.4) \times 10^{30}$ | $(1.7 \pm 1.6) \times 10^{-7}$ | $> 23.6$ | $2.8 \pm 1.4$ | $358 \pm 18$ | $> 20 \pm 15$ |
| 5593444799901901696 | $(5.2 \pm 4.7) \times 10^{26}$ | $(4.2 \pm 2.9) \times 10^{-8}$ | $31.1^{+1.9}_{-1.6}$ | $2.6 \pm 0.8$ | $1506 \pm 120$ | $15 \pm 10$ |
| 6328149636482597888 | $(7.7 \pm 7.3) \times 10^{23}$ | $(3.6 \pm 2.7) \times 10^{-10}$ | $40.0^{+1.5}_{-1.8}$ | $3.3 \pm 0.9$ | $816 \pm 10$ | $384 \pm 13$ |
| 3263804373319076480 | $(7.5 \pm 7.4) \times 10^{29}$ | $(4.1 \pm 4.0) \times 10^{-7}$ | $28.3^{+3.8}_{-7.8}$ | $2.8 \pm 0.5$ | $291 \pm 13$ | $32 \pm 30$ |
| 6601396177408279040 | $(4.1 \pm 0.7) \times 10^{22}$ | $(1.3 \pm 0.2) \times 10^{-10}$ | $41.2^{+0.4}_{-0.3}$ | $2.6 \pm 0.5$ | $652 \pm 50$ | $162 \pm 49$ |
| 6588211521163024640 | $(8.5 \pm 8.4) \times 10^{28}$ | $(1.5 \pm 1.4) \times 10^{-7}$ | $33.4^{+5.7}_{-8.4}$ | $2.4 \pm 0.4$ | $779 \pm 70$ | $63 \pm 60$ |
| 5870569352746779008 | $(7.1 \pm 4.0) \times 10^{27}$ | $(2.6 \pm 0.9) \times 10^{-8}$ | $27.4^{+0.8}_{-0.9}$ | $8.9 \pm 0.3$ | $1164 \pm 25$ | $65 \pm 9$ |
| 3104145904761393408 | $(4.8 \pm 4.7) \times 10^{25}$ | $(3.0 \pm 2.6) \times 10^{-9}$ | $34.5^{+3.5}_{-2.2}$ | $3.0 \pm 0.1$ | $515 \pm 15$ | $39 \pm 30$ |
| 4318465066420528000 | $(9.4 \pm 3.7) \times 10^{24}$ | $(5.2 \pm 1.0) \times 10^{-10}$ | $35.3^{+0.5}_{-0.4}$ | $32.7 \pm 0.8$ | $591 \pm 6$ | $566 \pm 3$ |

Although observing emission from the BH candidates is important, we emphasize that the critical test for registering manifestations of an event horizon is the detection of fast variations in the emission of plasma accreting onto a BH. The flare amplitude for a given accretion rate can reach a level of 5.5% of the luminosity in the X-ray range, making it possible to detect such events. Note that when magnetic field lines in the current sheets reconnect, their maximum Lorentz factor may reach $10^4-10^5$; the flares may therefore be detected by instruments with nanosecond and microsecond temporal resolution. Thus, there are possibilities of registering the emission of BHs in different wavelength ranges and with different temporal characteristics, and therefore, it may be possible to detect observational manifestations of their horizons.

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lisa.chmyreva@mail.ru