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

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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 the possibility of direct detection of both stationary and variable halo emission around the BHs.

Keywords: black hole physics; accretion; stars: black holes; methods: observational

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1 Introduction

According to current evolutionary predictions, the number of isolated stellar-mass black holes (BHs) in our Galaxy reaches 10^8 (Wiktorowicz et al. 2019). Detecting manifestations of their event horizons, and therefore proving their existence, is very important: horizons are a generic feature of all BHs (Beskin et al. 2008). 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 be obtained only 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 compared to 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 there is no interaction 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 nearly constant over 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 (Shvartsman 1971; Bisnovatyi-Kogan & Ruzmaikin 1974; Meszaros 1975; Ipser & Price 1982).

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

2 Sample binaries and calculations

Recently, several non-interacting binaries comprising a compact object and a main sequence star have been reported by various authors (El-Badry et al. 2023; Chakrabarti et al. 2023; Andrews et al. 2022; Shahaf et al. 2023; Tanikawa et al. 2023; Gaia Collaboration et al. 2024; Jayasinghe et al. 2021) based on Gaia DR3[1] data. For our analysis, we selected 17 wide non-interacting pairs with compact objects which masses allow us to assume that they might be BHs. Some lower-mass compact objects that may be neutron stars were also considered, if their mass uncertainties allow the possibility that these objects could be more massive. The primary objects in the sample binaries

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

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 (Bondi & Hoyle 1944; Shvartsman 1971; Beskin & Karpov 2005):

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

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 total space velocities of the BHs from their Keplerian orbital motions and the system center-of-mass velocity. The local ISM densities were estimated from the G-Tomo[2] Galactic extinction maps taking into account stellar winds, calculated assuming spherically-symmetric wind from a star of the corresponding spectral type. 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 speeds of sound in the surrounding gas. The resulting luminosities, accretion rates, and expected visual magnitudes are presented in Table 1.

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

Source ID Gaia DR3	L erg s^{-1}	$\dot{m}$ $\dot{M}/\dot{M}_{Edd}$	m_V Mag	M $M_\odot$	D pc	V 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 ± 0.2	480 ± 4	77 ± 12
4314242838679237120	$(7.5 \pm 7.4) \times 10^{30}$	$(1.7 \pm 1.6) \times 10^{-7}$	$23.6^{+3.9}_{-5.1}$	2.8 ± 1.4	358 ± 18	20 ± 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 ± 0.8	1506 ± 120	15 ± 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 ± 0.9	816 ± 10	384 ± 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 ± 0.5	291 ± 13	32 ± 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 ± 0.5	652 ± 50	162 ± 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 ± 0.4	779 ± 70	63 ± 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 ± 0.3	1164 ± 25	65 ± 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 ± 0.1	515 ± 15	39 ± 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 ± 0.8	591 ± 6	566 ± 3

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

3 Results and discussion

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. However, several of them may be within the sensitivity range of already operating and planned instruments. (e.g., JWST, GMT, MILLIMETRON, TMT, ELT). In particular Gaia DR3 4314242838679237120, 3263804373319076480, and 5870569352746779008 show promise in that regard.

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 maximal Lorentz factor may reach 10^4–10^5; therefore, the flares may 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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