ВАК 2024
MODERN ASTRONOMY:
FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES
300 years
Russian Academy of Sciences

A sphere or a disk? Accretion of gas onto isolated stellar-mass black holes

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Abstract. The most crucial problem in constructing a coherent model of the universe is the behavior of spacetime in the vicinity of the event horizons of black holes (BH). These regions can be accessible to direct observations only at low rates of spherical accretion. Based on the analysis of the current characteristics of interstellar gas turbulence, it has been shown that the spherical mode of accretion, unlike the disk mode, occurs at sufficiently low densities of the medium (excluding clouds and "hot" zones). In this case, disks can form only around virtually stationary Kerr and Schwarzschild BHs.

Keywords: stars: black holes; accretion, accretion disks; ISM: clouds

DOI: 10.26119/VAK2024.095

SAO RAS, Nizhny Arkhyz, Russia 2024 https://vak2024.ru/

1 Introduction

Despite extensive research, the quest for a quantum theory of gravity remains unresolved. This is highlighted by physical paradoxes and their proposed resolutions, often related to near black hole (BH) event horizons (EHs). BHs with their intense gravitational fields serve as critical testing grounds for new and old (e.g., General Relativity) macroscopic theories (Will 2006), and methods of quantizing gravity. A significant issue is the paradox of information loss in BHs (Hawking 2005), leading to numerous theoretical ideas, such as a firewall near the EH (high-energy quanta that destroy information of matter accreting onto the BH (Almheiri et al. 2013) and BH complementarity, where an observer can detect information either approaching the horizon or inside the BH, with these observations being mutually incompatible (Susskind et al. 1993). These theories remain untested experimentally. Direct detection of the EH and its surroundings is necessary, specifically by registering photons emitted from the immediate vicinity of the EH. High accretion rates in galactic cores and binary X-ray systems obscure the EH, but solitary stellar-mass BHs might provide accessible horizons due to low interstellar medium (IM) accretion rates and peculiar velocities but only for spherical accretion (Beskin & Karpov 2005).

This study focuses on feasibility of spherical accretion for observing EHs, considering modern understandings of the structure and dynamics of the IM.

2 Accretion onto a Schwarzschild black hole

Davies & Pringle (1980) considered accretion onto a supersonic BH, taking into account the inhomogeneity of IM. Assuming velocity and density gradients are small, it was found that accretion is still described by the Bondi–Hoyle formula and the specific angular momentum of the captured material is zero. However, this is generally not true, and angular momentum can be significant. This specific angular momentum is $l_m = \frac{1}{4}\mathit{\Delta} V_{r_c}$ (Illarionov & Sunyaev 1975), where $\mathit{\Delta} V$ is the change in velocity at the distance $2r_c$, $r_c = 2GM/(V^2 + c_s^2)$ (Bondi & Hoyle 1944), and c_s is the speed of sound. Numerical simulations have led to a realistic expression for the specific angular momentum $l \sim 0.1 l_m$ (Ruffert 1999).

For spherical accretion, the specific angular momentum of captured material must be less than it is in the last stable orbit of the BH, i.e. $l < \sqrt{3} c r_g$ for the Schwarzschild metric (Zeldovich & Novikov 1971). Then,

$$\mathit{\Delta} V < 40\sqrt{3}\frac{V_0^2}{c}, \text{ where } V_0 = \sqrt{V^2 + c_s^2}. \tag{1}$$

Analysis of new data in the recent studies of Lee & Lee (2019); Chepurnov & Lazarian (2010) demonstrates a good agreement of the turbulence spectrum with the

Kolmogorov spectrum on scales of tens of meters, which is crucial for estimating velocity dispersion and density fluctuations. As we will see, for practically any BH velocity, turbulent motions in the IM cannot hinder spherical accretion. Moreover, density fluctuations also cannot hinder it. From the work of Armstrong et al. (1995),

$$\frac{\Delta\rho}{\rho} \sim \left(\frac{R}{1\ \mathrm{pc}}\right)^{11/6},$$

substituting into $l_m = \dfrac{\Delta\rho}{4\rho} V_K r_c$, where $V_K = V_0/\sqrt{2}$ is the Keplerian speed at the capture radius. At the distance of $2r_c$, we obtain: $V_0 > 2.80 M_{10}^{0.393}$ [km/s][1] for specific momentum of the captured gas not exceeding that of the last stable orbit.

2.1 Location of a black hole in cold clouds

Suppose the molecular cloud has a temperature T and concentration n. For cold and dense clouds ($T \sim 100$ K, $n \sim 100\ \mathrm{cm}^{-3}$), assuming a Kolmogorov spectrum of turbulence, the following expression for ΔV was obtained by Cen (2021)

$$\Delta V = \sqrt{\frac{14}{11}} \left(\frac{68 K r_c}{11 G M^2}\right)^{1/5} \sigma_{\mathrm{pc}} \left(\frac{2r_c}{1\ \mathrm{pc}}\right)^{\gamma}. \tag{2}$$

Suppose the cloud is a sphere with a radius $2r_c$, then the total kinetic energy is $K = 16\pi n r_c^3 kT$. Let $M_{10} = M \times 10^{-1}\ \mathrm{M}_\odot$, after a bit of algebra[2] with eq. $(1, 2)$. If the cloud is located in the center of the galaxy, then $\sigma_{\mathrm{pc}} \simeq 1.03$ km/s, $\gamma \simeq 0.63$ (Cen 2021), we obtain $V_0 > 4.15 M_{10}^{0.212}$, or $V > 3.97$. However, if the cloud is located in the galactic disk, then $\sigma_{\mathrm{pc}} \simeq 0.46$, $\gamma \simeq 0.57$. We get $V_0 > 3.71 M_{10}^{0.205}$, or $V > 3.52$.

2.2 Location of a black hole in warm clouds

In warm clouds ($T \sim 10^3$ K, $n \sim 0.1\ \mathrm{cm}^{-3}$), ΔV could be expressed as (Larson 1981)

$$(\Delta V)^2 = 1.1 \times \left(\frac{2r_c}{1\ \mathrm{pc}}\right)^{0.76} \ [\mathrm{km/s}]^2, \tag{3}$$

by substituting eq. (1), we get $V_0 > 16.59 M_{10}^{0.138}$, or $V > 16.16$ (Beskin & Karpov 2005).

3 Accretion onto a Kerr black hole

Similar steps can be applied to a Kerr BH, but then the last stable orbit will depend on a, the specific angular momentum parameter of the BH, and its direction of

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[1] All the estimates are given in [km/s], if not written otherwise

[2] https://github.com/dimicorn/accretion_bh

rotation. If $a > 0$ (“+”), the specific angular momentum of captured material must be $l_+ < cr_g/\sqrt{3}$, otherwise $a < 0$ (“−”), $l_- < 11cr_g/\sqrt{3}$ (Zeldovich & Novikov 1971). Then,

$$\Delta V_+ < \frac{40\sqrt{3}}{3}\frac{V_0^2}{c}, \qquad \Delta V_- < \frac{440\sqrt{3}}{3}\frac{V_0^2}{c}. \tag{4}$$

Substituting it into eq. $(2,3)$ we obtain estimates for cold clouds in the center of the galaxy: $V_{0+} > 5.20M_{10}^{0.212}$, or $V_+ > 5.06$; $V_{0-} > 3.17M_{10}^{0.205}$, or $V_- > 2.95$. Doing the same for cold clouds in the galactic disk, we get $V_{0+} > 4.67M_{10}^{0.212}$, or $V_+ > 4.52$; $V_{0-} > 2.82M_{10}^{0.205}$, or $V_- > 2.56$. And we obtain estimates for warm clouds: $V_{0+} > 24.69M_{10}^{0.138}$, or $V_+ > 24.41$; $V_{0-} > 10.36M_{10}^{0.138}$, or $V_- > 9.67$.

4 Summary

We have shown that for isolated BHs of stellar masses at typical velocities of Galactic stars (less than 15 km/s), spherical accretion of IM is realized. The obtained result allows to identify areas in the Galaxy where isolated BHs are localized, whose EHs (ergospheres) are in principle accessible for observations. Searches in these zones for peculiar objects with observational manifestations predicted for accreting isolated stellar-mass BHs may lead to the discovery of the latter.

Acknowledgements. The work was partially carried out within the framework of the state assignment of the SAO RAS, approved by the Ministry of Science and Higher Education of the Russian Federation, and partially supported by the SAL Program of the KFU.

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