ZAMONAVIY ILM-FAN: FANLARARO INTEGRATSIYA VA INNOVATSION TARAQQIYOT

RESPUBLIKA ILMIY-AMALIY KONFERENSIYA

MAQOLA VA TEZISLAR TO‘PLAMI



“FANLARARO ILMIY TADQIQOTLAR” ILMIY-AMALIY METODOLOGIK JURNALI

“ZAMONAVIY ILM-FAN: FANLARARO INTEGRATSIYA VA INNOVATSION TARAQQIYOT” MAVZUSIDAGI RESPUBLIKA ILMIY-AMALIY KONFERENSIYA

MAQOLA VA TEZISLAR TO‘PLAMI
2026-yil 12-noyabr

Toshkent – 2026

ISSN:3093-9240

“Zamonaviy ilm-fan:fanlararo integratsiya va innovatsion taraqqiyot” mavzusidagi respublika ilmiy-amaliy konferensiya maqola va tezislar to‘plami (2026-yil 12-noyabr) – T.: FANLARARO ILMIY TADQIQOTLAR, 2026.

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SPECTRAL AND IMAGING SIGNATURES OF ACCRETION FLOWS AROUND ROTATING BLACK HOLES

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Annotatsiya. Akkretsiyalanuvchi qora tuynuklar elektromagnit nurlanish yordamida gravitatsiyaning kuchli maydon rejimini o‘rganish imkonini beruvchi yagona laboratoriyalardir. So‘nggi o‘n yillikda kuzatuv ko‘rsatkichlarining bir-birini to‘ldiruvchi ikki guruhi rivojlandi. Birinchi guruh spektral kuzatuvlarni qamrab oladi: diskning ichki qismidan keluvchi issiqlik kontinuumi, relyativistik effektlar tufayli kengaygan fluoressent chiziqlar, reverberatsion kechikishlar, shuningdek, so‘nggi yillarda rivojlangan rentgen qutblanishi va mikrokalorimetrik spektroskopiya. Ikkinchi guruh tasvirlashga asoslanadi: millimetr to‘lqin uzunliklaridagi o‘ta uzun bazali interferometriya (VLBI) M87* va Sgr A* qora tuynuklarining hodisalar gorizontlari atrofidagi gravitatsion linzalanishga uchragan nurlanish tuzilmasini fazoviy ajratish imkonini bermoqda. Mazkur ishda nazariy asoslar — Kerr fazo-vaqtidagi geodezik chiziqlar, yupqa va issiq akkretsion oqimlar hamda umumiy relyativistik magnitogidrodinamik (GRMHD) modellashtirish — bayon etiladi. Shuningdek, 2026-yilgacha bo‘lgan kuzatuv yutuqlari umumlashtirilib, ochiq muammolar, dissertatsiya tadqiqotining maqsadi, vazifalari va usullari belgilab beriladi.

Kalit so‘zlar: qora tuynuk; Kerr metrikasi; akkretsion disk; eng ichki barqaror doiraviy orbita (ISCO); temirning Kα chizig‘i; qora tuynuk soyasi; foton halqalari; Event Horizon Telescope; XRISM; IXPE.

Аннотация. Аккрецирующие чёрные дыры являются единственными лабораториями, позволяющими исследовать сильнополевой режим гравитации с помощью электромагнитного излучения. За последнее десятилетие получили развитие две взаимодополняющие группы наблюдаемых характеристик. Первая связана со спектральными наблюдениями: тепловым континуумом внутренней части диска, релятивистски уширенными флуоресцентными линиями, реверберационными задержками, а в последние годы — также с рентгеновской поляризацией и микрокалориметрической спектроскопией. Вторая группа основана на получении изображений: интерферометрия со сверхдлинными базами (VLBI) на миллиметровых длинах волн позволяет пространственно разрешать гравитационно линзованное излучение вблизи горизонтов событий чёрных дыр M87* и Sgr A*. В работе изложены теоретические основы

исследования: геодезические в пространстве-времени Керра, тонкие и горячие аккреционные потоки, а также моделирование в рамках общей релятивистской магнитогидродинамики (GRMHD). Обобщены достижения наблюдательной астрономии по состоянию на 2026 год, обозначены открытые проблемы и сформулированы цель, задачи и методы диссертационного исследования.

Ключевые слова: чёрная дыра; метрика Керра; аккреционный диск; самая внутренняя устойчивая круговая орбита (ISCO); линия железа Kα; тень чёрной дыры; фотонные кольца; Event Horizon Telescope; XRISM; IXPE.

Abstract. Accreting black holes are the only laboratories in which the strong-field regime of gravity can be probed using electromagnetic radiation. Two complementary families of observables have matured over the past decade. The first comprises spectral diagnostics: the thermal continuum of the inner disk, relativistically broadened fluorescent lines, reverberation lags, and, more recently, X-ray polarization and microcalorimeter spectroscopy. The second comprises imaging diagnostics: very-long-baseline interferometry (VLBI) at millimetre wavelengths now spatially resolves gravitationally lensed emission around the event horizons of M87* and Sgr A*. This thesis outlines the theoretical framework, including Kerr geodesics, thin and hot accretion flows, and general relativistic magnetohydrodynamic (GRMHD) simulations. It summarizes observational advances through 2026, identifies open problems, and sets out the aim, objectives, and methods of the dissertation research.

Keywords: black hole; Kerr metric; accretion disk; innermost stable circular orbit (ISCO); iron Kα line; black-hole shadow; photon rings; Event Horizon Telescope; XRISM; IXPE.

INTRODUCTION

According to the no-hair theorems of general relativity (GR), an isolated, stationary black hole is fully described by its mass M, angular momentum $J = a^*GM^2/c$ and electric charge; the resulting spacetime is the Kerr metric [1]. Astrophysical black holes are never observed directly. We observe radiation from gas falling towards them: X-ray binaries such as Cygnus X-1, and active galactic nuclei (AGN) powered by supermassive black holes of 10^6–10^{10} $M_\odot$. Emission produced within a few gravitational radii $r_g = GM/c^2$ of the horizon carries the imprint of the spacetime through gravitational redshift, Doppler boosting, light bending and frame dragging.

Relevance of the topic. The topic is timely for four reasons:

Horizon-scale imaging is now an observational reality. The Event Horizon Telescope (EHT) produced the first images of M87* [2] and Sgr A* [3], followed by polarimetric images of both. Observations in 2017, 2018 and 2021 show a ring of persistent diameter 43.9 ± 0.6 μas, but with brightness and polarization patterns that change from year to year [4].

X-ray spectroscopy has entered the microcalorimeter era. The Resolve instrument on XRISM reaches ~5 eV resolution at 6 keV and, for the first time, separates the broad iron line from narrow emission and wind absorption features [5]. It has also exposed a strong dependence of spin estimates on the assumed reflection model [6].

X-ray polarimetry constrains the geometry of the inner flow. IXPE measured a polarization degree of ~4% in Cyg X-1, with the angle aligned with the radio jet, ruling out compact "lamp-post" corona geometries [7].

Strong-field tests of gravity require joint modelling. Spectra and images are sensitive to different combinations of mass, spin, inclination, flow physics and deviations from the Kerr metric [10]; only a joint treatment can break these degeneracies.

Aim. To develop a unified general-relativistic framework that computes the spectral and imaging signatures of accretion flows around rotating black holes, and to determine how well spectra and images, separately and jointly, constrain black-hole parameters and possible deviations from the Kerr metric.

Objectives:

To develop a ray-tracing code for null geodesics in Kerr and other spacetimes, validated against analytic results for the critical curve, the ISCO and the redshift factor.

To compute thermal continuum spectra of Novikov–Thorne disks and analyse their dependence on spin, inclination and deviation parameters.

To compute relativistically broadened Fe Kα line profiles and investigate degeneracies between spin, inclination, emissivity profile and deviation parameters.

To construct images of thin disks and of thick, optically thin flows, including the direct image and the n = 1, 2 photon rings, and to quantify the relation between the observed ring diameter and the critical curve.

Object of research: accretion flows around stellar-mass and supermassive black holes.

Subject of research: the spectral (continuum, iron line) and imaging (shadow, photon rings, ring asymmetry) signatures of these flows and their dependence on black-hole parameters and spacetime geometry.

MAIN PART

Theoretical background

Kerr spacetime and characteristic radii. In Boyer–Lindquist coordinates (G = c = 1), three radii control the appearance of an accretion flow: the event horizon, the circular photon orbits and the innermost stable circular orbit (ISCO) [8]:

$r_+ = M + \sqrt{(M^2 - a^2)}$, $r_ISCO = M\,[3 + Z_2 \mp \sqrt{((3 - Z_1)(3 + Z_1 + 2Z_2))}]$

The ISCO moves from 6M for a Schwarzschild black hole to ≈ 1.24M for a* =

0.998, and to 9M for a maximally retrograde disk. The radiative efficiency of a thin disk, η = 1 − E_ISCO, grows from 5.7% at a* = 0 to 32% at a* = 0.998. This steep dependence of r_ISCO and η on spin is the physical basis of all spectral spin measurements.

Photon motion and photon rings. Null geodesics in Kerr spacetime are integrable thanks to the Carter constant. Photons on unstable spherical orbits form the critical curve, whose interior is called the black-hole shadow. For a Schwarzschild black hole it is a circle of radius 3√3M ≈ 5.2M. At the low inclination of M87* (i ≈ 17°) its diameter shrinks by less than 8% between a* = 0 and 0.998, so the shadow size is a robust mass indicator but a weak spin indicator. Light that orbits the hole n/2 times forms nested photon rings, each demagnified by a factor e^(−γ) [9]. Their shape is governed mainly by the spacetime, which makes them prime targets for spin measurements and tests of GR [9].

Accretion flow models. The thin, optically thick α-disk and its relativistic generalisation describe radiatively efficient accretion at L ~ 0.01–0.3 L_Edd and underlie the continuum-fitting method. Near the Eddington limit, slim disks form and the inner edge is no longer sharp at the ISCO. At low accretion rates the gas cannot cool and forms a hot, geometrically thick advection-dominated flow (ADAF/RIAF); Sgr A* and M87* are prototypes. The magnetorotational instability and the Blandford–Znajek process are evolved self-consistently in GRMHD codes, which distinguish SANE and MAD regimes.

*Thermal continuum***.** In the soft state, with independent mass, distance and inclination, the fitted inner-disk radius yields the spin. For Cyg X-1 (M ≈ 21 M⊙) continuum fitting gives a* > 0.9985.

*Relativistic reflection and the iron Kα line***.** Coronal X-rays illuminating the disk produce an Fe Kα line at 6.4–6.97 keV, broadened and skewed near the black hole by Doppler shifts and gravitational redshift. XRISM data on Cyg X-1 analysed with RELXILL give a* ≃ 0.98 and i ≃ 63° [5], while Comptonisation-based models give a low spin, a* = 0.0 (+0.17) [6]. The spin of the best-studied stellar-mass black hole is therefore strongly model-dependent.

*Timing and polarimetry***.** Reverberation lags measure light-travel distances of a few r_g, and quasi-periodic oscillations are linked to relativistic precession of the inner flow. IXPE measured 4.0 ± 0.2% polarization in the hard state of Cyg X-1, showing that the X-ray plasma is extended perpendicular to the jet [7].

Imaging signatures

At 230 GHz the EHT resolves structures of ~20 μas. The 2017 image of M87* shows an asymmetric ring of diameter 42 ± 3 μas, giving a mass of (6.5 ± 0.7) × 10^9 M⊙ [2]. For Sgr A* the ring is 51.8 ± 2.3 μas and the mass 4.0 (+1.1/−0.6) × 10^6 M⊙

[3]. Spiral polarization patterns indicate strong, ordered magnetic fields and favour MAD models. The shadow size agrees with GR to within ≈ 17% for M87* [10] and ~10% for Sgr A*. The next-generation EHT and the BHEX mission aim to detect the n = 1 photon ring and measure spin almost independently of flow physics [9].

Model dependence of spectral spin measurements: different methods, and even different reflection models, give different spins for the same source [6].

Geometry of the corona and inner flow: polarization, timing and reflection favour different geometries.

Connecting image features to spacetime: the relation between the observed ring and the critical curve depends on the emission profile and electron thermodynamics.

Variability: Sgr A* variability and the polarization reversal in M87* are not reproduced by standard GRMHD models.

Tests of the Kerr hypothesis: deviations from Kerr are degenerate with spin, inclination and flow parameters.

Research methods. The work uses analysis of geodesic motion via conserved quantities and the Carter constant; backward ray tracing from the observer’s screen; the relativistic thin-disk model; covariant radiative transfer for optically thin synchrotron emission; and statistical comparison with observations (χ^2 and Markov-chain Monte Carlo). Computations are performed in Python/C++ and Wolfram Mathematica.

CONCLUSION AND RECOMMENDATIONS

Recent observations — EHT images, XRISM microcalorimeter spectra and IXPE polarimetry — have greatly expanded our ability to study black holes in the strong-field regime. Yet spectral spin estimates remain strongly model-dependent, and the observed ring is emission from the flow rather than the critical curve itself. Developing theoretical models that predict spectral and imaging signatures within a single, self-consistent framework is therefore a relevant problem of modern relativistic astrophysics.

Scientific significance — clarifying how accretion-flow physics and spacetime geometry each shape the observed spectra and images, which is required for reliable spin measurements and strong-field tests of GR.

Practical significance — the numerical tools and model predictions can be applied to XRISM, IXPE, NuSTAR and EHT data, to planning next-generation EHT and BHEX observations, and to university courses on general relativity and relativistic astrophysics.

Reliability of the results is ensured by rigorous GR methods, validation of the codes against known analytic solutions (the Schwarzschild shadow radius $3\sqrt{3}M$, the ISCO radii, the Kerr critical curves), recovery of known results in the Kerr limit of

alternative spacetimes, and agreement with published results and observational data.

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Muassis: “Fanlararo ilmiy tadqiqotlar” MCHJ
“Fanlararo ilmiy tadqiqotlar” MCHJ nashriyotida nashrga tayyorlandi va jurnalning rasmiy veb-saytiga joylashtirildi
Tahririyat manzili: Toshkent shahri, Sergeli tumani, Yangi Bunyodobod MFY, 8-uy
Rasmiy veb-sayt: https://fanlararotadqiqotlar.uz/index.php/conference/r
E-mail: publisher@fanlararotadqiqotlar.uz